Original Research Article

EFFECTIVENESS OF PHOSPHORUS SOLUBILIZING BACTERIA ON ENHANCING PHOSPHORUS AVAILABILITY FROM MINJINGU PHOSPHATE ROCK TO MAIZE IN SLIGHTLY ACID TO NEUTRAL SOILS

Abstract

The aim of this one-year field study was to evaluate the impact of phosphorus solubilizing bacteria (PSB) on increasing the availability of phosphorus locked up in insoluble Minjingu phosphate rock for the maize crop (Zea mays L.) in high soil pH. The study was carried out during one wet season in Nghumbi and Mlali villages in Kongwa District in the Dodoma Region, Tanzania. Based on the pH of their soil and the limiting nutrients, two farms from Mlali village and five from Nghumbi village were chosen at random for field trials. To determine the fertility status, composite soil samples were collected from the chosen farms and examined in a lab. Target treatments included the application of PSB inoculum in combination with various rates of Minjingu phosphate rock (MPR) (0, 20, 30, 40, and 60 KgP ha-1) as a basal fertilizer, placed beneath maize seed and covered with a thin layer of soil. Using a fully randomised block design, the treatments were set up three times. Inadequate levels of N, P, K, and Zn were found in the research area's soil samples. Results indicated the main effect of fields' characteristics from field No.2 had the highest yield to other fields with significantly (*P*< 0.001) highest grain yield being 4.4 t ha^{-1}, biological yield of 5.6 t ha^{-1}, and Straw P uptake of 19.63 kg ha^{-1}. Using P or an inoculant (Mx) produced a negligible yield of grain and straw, according to the major effect of treatments. For the studied variables, none of the treatments showed any significant (P =0.427) interaction effects. An intriguing revelation that the study's maize response to native P is provided by interaction effects area is a factor of soil and amount of P released to the soil. We recommend more research on PSB for more than one season in high soil pH before ascertaining the technology to farmers.

Keywords: Bio-fertilizer; cropping systems; Food crops; Soil fertility; Tanzania.

1 Introduction

Along with other nutritional elements, phosphorus (P) is the macronutrient that often restricts plant growth and the final output. As a plant ages, phosphorus that has been absorbed is moved to its fruiting sections, where the production of seeds necessitates a significant energy expenditure. Soil phosphorus deficits affect normal crop maturity as well as seed development. The most common nutrient deficiency in tropical African soils is phosphorus, which significantly restricts Tanzania's ability to produce maize. According to Nhunda et al. (2024), low-access P is a problem in Kongwa district, as evidenced by the soil's acidic and alkaline conditions. Low P in the parent material and high P fixation by iron and aluminum oxides in acid are the causes of low-soil P (Silesh *et al.,* 2022) and precipitation by calcium in alkaline soils (Adnan *et al*., 2017).

Since the 1960s, Tanzania has paid close attention to the use of phosphate rock (PR), such as Minjingu phosphate rock (MPR), as an alternative P source (Anderson, 1993; Ikerra et al., 1994; Szilas, 2002). Previous research findings indicated that MPR's residual effect made it superior to subsequent crops in the field after the original application (Ikerra et al., 2007). The prolonged and continual gradual release of P from MPR is the cause of the high residual and long-lasting effects. Numerous studies have documented PR's capacity to release P, but little is known about how high/alkaline pH influences the material's ability to dissolve in soil.

Due to the lack of solubilization required to liberate P for crop use, PR is difficult to use for crop production in neutral (pH 6.6–7.3) and alkaline (pH >7.3) soils. As soil pH climbs to 6.2, PR solubilizes swiftly at pH ranges of 4.9 to 5.5. According to Anderson *et al*. (2018), PR becomes completely insoluble at pH values higher than 6.1. Bolan and Hedley (1990) employed three forms of PR: Jordan PR (JPR), North Carolina PR (NCPR), and Nauru PR (NPR). The degree of PR dissolving at each pH was determined to follow the following order, based on the decreasing order of the chemical reactivities: As soon as the pH dropped below six, from NCPR>JPR>NPR.5 to 3.9, the dissolution of PRs increased from 29.3% to 83.5%, from 18.2% to 78.9%, and from 12.5% to 60.3% for NCPR, JPR, and NPR, respectively.

In contrast as the pH decreased from 6.5 to 3.9, the proportional of dissolved P extracted by 0.5 M $NaHCO_3$ decreased from 38% to 5% and the proportion of P taken up by ryegrass plant decreased from 46% to 7%(Balon and Hedley, 1990). The decrease in plant available P corresponds to an increase in adsorption of inorganic P in low pH (Balon and Hedley, 1990). Balon and Hedley (1990) further noted that an increase in pH was associated in decreased degree of PR dissolution. Warren *et al*. (2009) reported that dissolution of P from PR was insignificant at pH >6.1 while citing out the causes being pH in the media and P sorption.

It is necessary to investigate a unique mechanism in order to release the locked-up P in the insoluble PR when it is applied at high soil pH. It has been reported that phosphorus solubilising bacteria convert insoluble to soluble P from PR by releasing low-weight molecular organic acids such as acetic, formic, propionic, lactic, glycolic, and fomic acids (Zaworotko *et al*., 2019). Carboxyl and hydroxyl groups from organic acids are capable of chelating with cations bound to phosphate thereby converting it into soluble forms (Zaworotko *et al*., 2019). Additionally, the bacteria produce acidity by evolving carbon dioxide (CO2), which causes calcium phosphates to become soluble (Yousefi et al., 2011). It has been demonstrated that in soils with high pH values (>6.2), phosphorus-solubilizing bacteria improve P availability, hence promoting crop growth (Bhattacharyya and Jha, 2012).

According to reports, inoculating PSB into soil contaminated with metals increased maize production (Jiang et al., 2008). Linu et al. (2009) discovered the nodulation, root, and shoot biomass of the B-inoculated maize and cowpea plants. *Compared to the control group, there were notably more Cepacta.* While the benefits of bacteria in raising P availability from PR are well established in acidic soils, they have not been consistently shown in Tanzanian alkaline soil studies (Zaidi et al., 2009). There is a dearth of information on high pH soils, and the outcomes of the little that is available are evasive or unclear. The study aims to increase maize output in Dodoma's Kongwa district by utilizing additional P from Minjingu PR, which will be released into its alkaline soils. The precise goals were to assess maize performance, calculate P uptake by maize, and determine how well PSB dissolved MPR in high-pH soil.

Maize is one of the key staple food crops and major cereal consumed in Tanzania. It is estimated that the annual per capita consumption of maize in Tanzania is 112.5 kg and national maize consumption is estimated to be three million tons per year (Giller *et al*. 2021a). The crop is annually on an average of two million hectares or about 45% of the cultivated area in Tanzania. The Dodoma region is a semi –arid area and therefore maize production is hampered by drought, among other factors. Average maize production in Dodoma is about 0.4 tons per hectare which is far below the national average yield of just over 1 ton per hectare (Giller *et al*. 2021a). This study therefore was set in this region with the aim rising up maize yield by enhancing phosphorus availability to maize crop.

P demand by crops needs to be taken into account especially in smallhoder farmers. Compared to perennial crops, crops with intense and short cycle growth, such as maize, require higher P levels in soil solutions and faster absorbed P replenishment for optimal production (Lino et al., 2018). But because there is never enough phosphorus in agricultural soils, people must rely on artificial fertilizers, which can have negative financial and environmental effects. This manuscript investigates the potential synergy between Minjingu rock phosphate and phosphorus solubilizing agents in high soil pH as a sustainable and environmentally friendly way to increase phosphorus availability for maize cultivation (Hengl et al., 2017).

Hypothesis: Application of phosphorus solubilising bacteria will significantly enhance the availability of phosphorus from Minjingu phosphate rock to maize in high Ph soil conditions, resulting to improved maize growth and yield.

2 Materials and Methods

2.1 Description of the study area

This study was conducted in Mlali and Nghumbi villages of Kongwa district, Dodoma region located within the semi-arid zone of Central Tanzania. Kongwa district is located between latitudes 5.47 to 6.26^{o}S and longitude 36.15 to 37.08^{o}E. Mlali village is located between latitude 6°16`22`` to 6°17`15``S and longitude 36°42`04`` to 36°47`26``E while Nghumbi village is located between latitude 6°18`17`` to 6°20`36``S and longitude 36°47`57`` to 36°50`58``E. The location of each experimental field is indicated by using central points as shown in Table 1.

Table 1: Geographical locations of the studied fields in Kongwa Districts, Tanzania

Village	Farm No.	Coordinates	
Nhgumbi	1	S 06.31561	E 036.82605
	2	S 06.31456	E 036.82698
	3	S 06.31414	E 036.84106
	4	S 06.30932	E 036.83009
	5	S 06.30815	E 036.81939
Mlali	6	S 06.26317	E 036.74073
	7	S 06.26348	E 036.74657

The villages are characterised by medium altitude plains with some hill ranges, mainly medium textured soils with low to moderate fertility (Mowo*et al.,* 1993). Soils are diverse but dominated by highly weathered and classified as Chromic Luvisols with sandy loam texture tropical soils (Meliyo*et al.,* 2014).

The selected villages have undulating to rolling plains and plateaux with an altitude ranging from 700 to 900 metres above sea level (masl). Rains are usually erratic with variability in their onset, distribution, and intensity (Mongi *et al.,* 2010). The study area has the average annual rainfall ranging from 500 to 800 mm (Meliyo*et al.,* 2014). Seasonal distributions of rain can be very sporadic with 48% of the rain falling towards the end of the growing season giving little advantage to crop growth and yield (Kimaro *et al.,* 2009).

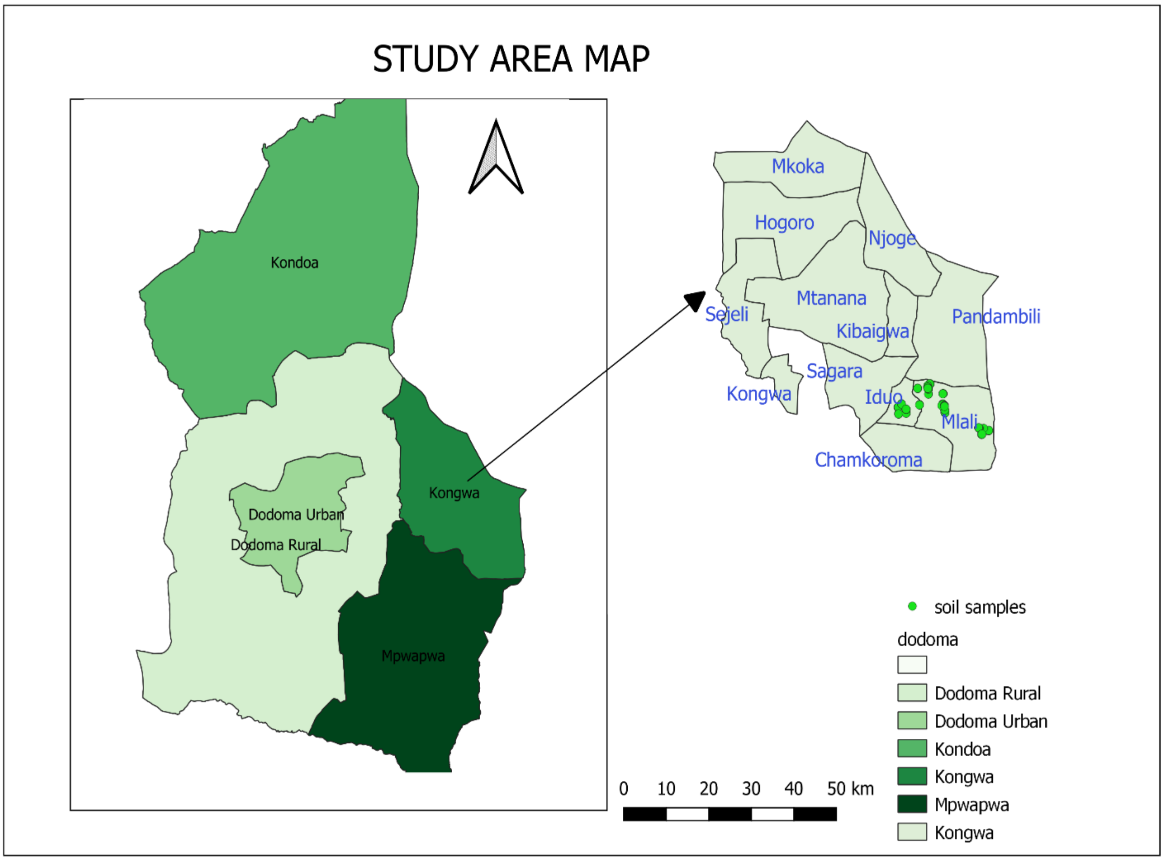

Figure 1: Map of Dodoma region showing study district and villages in which experiment was conducted

2.2 Site selection of the study site

In order to learn about the cropping history of the fields and to gain an understanding of the techniques involved in producing maize, such as the kinds utilized, planting dates, and establishment of a growing season, a reconnaissance mission was carried out in seven significant regions in the Kongwa district. Additionally, focus groups (FGDs) and consultative sessions with village leaders and individual farmers were held. This survey revealed that farmers employ local kinds of maize, the research area has two to three months of rainfall, and December is the ideal time to put up trials.

Composite soil samples were taken at 0–20 cm depths in 24 surveyed fields, which corresponded to the Kongwa district's maize-growing zones. After these soils were analyzed in a lab, a field study including maize as the test crop and PR injected with P-solubilizing bacteria was eventually limited to seven fields based on the pH of the soil. As shown in Figure 2, daily data on temperature and rainfall were gathered from November 2020 until April 2021, when the experiment came to a conclusion. When maize plants were in the experimental fields, there was no linear (polynomial) drop in temperature or rainfall.

As shown in Figure 2, daily rainfall data was gathered from the rainfall station that USAID erected in the experimental region as part of the IITA-Africa RISING ESA Project in 2019 from November 2020 to April 2021. Ten (10) day intervals are used to illustrate the rainfall data.

When maize plants were in the experimental fields, there was no linear (polynomial) drop in temperature or rainfall. The closest experimental location used by Casper (2002) to collect evapotranspiration data provided the evapotranspiration data.

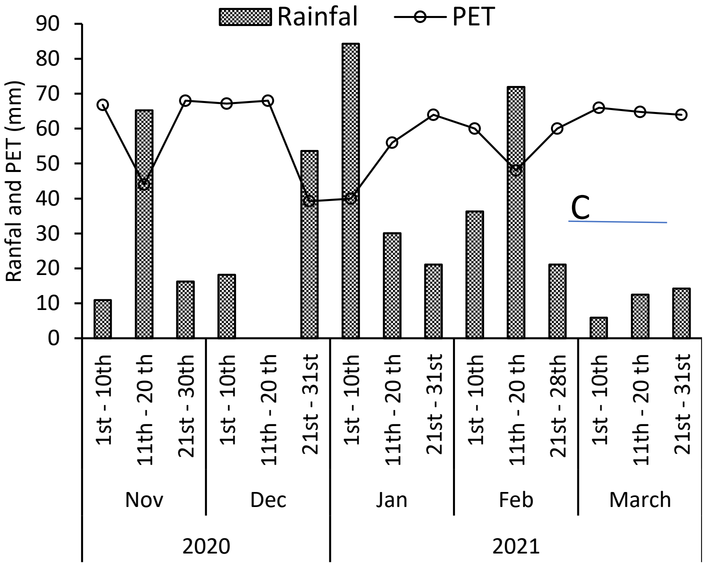

Figure 2: *Trends of rainfall (mm) and evapotranspiration in the study area during period of experimentation with maize crop – Kongwa district.L = shows the planting date, B = is the drought period during vegetative growth, C = drought period during flowering and grain filling*

Table 2: Identity of isolated PR-solubilizing species based on nucleotide database on American National Institute of Health (NIH) NCBI genetic database (GenBnk) (source: SUA soil laboratory published by Kwaslema, 2021).

Isolate	Species	Accession number	Nucleotide identity	Country	Source rhizosphere
Fg1	*Fusarium proliferatum*	MZ497514	100	Tanzania	Maize
Mk10	*Burkholderiasp*	MZ502221	99.9	Tanzania	Maize
NA19a	*Klebsiella sp*	MZ502673	99.9	Tanzania	Maize
Klm3	*Burkholderiasp*	MZ502220	99.9	Tanzania	Maize
MbMz1	*Klebsiella sp*	MZ502668	99.8	Tanzania	Maize
Sl-Sp1	*Klebsiella sp*	MZ502674	99.8	Tanzania	Sweet potato
NA4a	*Unidentified*			Tanzania	Irish potato
NA4b	*Klebsiella sp*	MZ502671	99.8	Tanzania	Irish potato
SUApp3	*Klebsiella sp*	MZ502675	99.7	Tanzania	Sweet pepper
MdG1	*Klebsiella varricola*	MZ502670	99.8	Tanzania	Banana

NA5	*Klebsiella varricola*	MZ502672	99.9	Tanzania	Sweet potato
MdE4	*Klebsiella varricola*	MZ502669	100	Tanzania	Common bean

2.3 Experimental design, treatment, and field experimentation

Seven fields (two at Mlali and five at Nghumbi) with the desired soil pH in the study area were selected. Trials using maize as a test crop in seven selected fields were established. The treatment combinations were PSB inoculum co-applied with MPR at different rates, as shown in table 2.

Table 3. Treatment combinations used in a study

S/N	Treatment	Treatment symbol	Description
1	T1	P_0M_0	treatment control
2	T2	$P_{30}M_0$	MPR at 30 kg ha^{-1}
3	T3	P_0M_x	Only PSB
4	T4	$P_{20}M_x$	MPR at 20 kg ha^{-1} with PSB
5	T5	$P_{40}M_x$	MPR at 40 kg Pha^{-1} with PSB
6	T6	$P_{60}M_x$	MPR at 60 kg Pha^{-1} with PSB

There were three replications of the treatments, for a total of eighteen plots. Using maize as the test crop and three replications or blocks of treatments in each of the seven fields, the study used a randomized complete block design (RCBD). Every test plot measured 4 m in length and 3 m in breadth, or 12 m^2. Between December 25th and 30th, two maize seeds (variety Situka) were planted in each hole. As a result, there were four rows and thirteen holes in a row, with a 90 cm gap between rows and a 30 cm gap within rows. Applying the PSB inoculum under maize seed, various rates of P from MPR (0, 20, 30, 40, and 60 kg ha-1) were combined with it as a basal fertilizer and adding a little layer of soil on top. Every planting hole received 5 mL of solution containing the inoculum. Limiting nutrients like N and S were fixed by using Yara Amidas, which was divided into two dressings: a basal dressing and a top dressing (N 40% and S 5.5%).

2.4 Data collection

2.4.1 Laboratory soil analysis

Before field selection and the commencement of field trials, the soils were assessed for total nitrogen using the micro-Kjedahl method (Bremner and Mulvaney, 1982). Available P was extracted using the Bray-1 method (1982), and its color was determined using a spectrophotometer using the molybdenum blue method (Murphy and Riley, 1962). Exchangeable K was found in ammonium acetate filtrates using a flame photometer. The same filtrate included exchangeable Ca and Mg, as determined by atomic adsorption spectrophotometry.

2.4.2 Laboratory analysis of plant samples

Following the completion of the plant growth cycle, fully grown maize plants were taken out of each plot, their individual biomass was measured, the cobs were threshed, and the dry grain weight was computed. In order to calculate P absorption and P utilization efficiency, the cobs and straws were chopped, cleaned, and processed in the lab using Moberg's (2002) guidelines for P concentration analysis. The P absorption by maize straw was then calculated using Equation 1's methodology.

$$\text{P uptake } (\text{kg ha}^{-1}) = \text{P conc. in straw } (1/100) \times \text{straw yield } (\text{kg ha}^{-1}) \times 1000 \qquad (1)$$

Equation 2's biomass yield per unit of nutrient uptake was used to calculate P uptake by straw.

$$\text{P uptake in straw} (\text{kg kg}^{-1}\text{P}) = \frac{\text{BY}_\text{f}}{\text{N}_\text{f}} \qquad (2)$$

Where BY_f is the biological/ straw yield (kg ha^{-1}) and N_f is the (P) uptake by the straw. Biological yield is defined as the total dry matter accumulation of a plant material.

Furthermore, P use efficiency (PUE) was calculated by using amount of P in straws/uptake and maize biomass yield as shown in Equation 3.

$$\text{Straw P use efficiency } (\mathbf{kg\ kg - 1}) = \frac{\text{Straw yield in kg}}{\text{Straw P uptake in kg}} \qquad (3)$$

2.4.3 Limiting nutrients of the study soils in Kongwa district

In order to comprehend the characteristics of each field under study and the particular nutrients that are likely to restrict crop growth and development, limiting nutrients for each field were selected and arranged based on farm number. The acquired soil data were used to assess each field's limiting nutrients and field features.

2.5 Statistical analysis

In assessing phosphorus concentration (% P), total P uptake, P use efficiency, biological yield, and grain yield the fixed main effects were the farmer's field characteristics and treatments, whereas blocks were treated as random effect. A TWO–WAY analysis of variance (ANOVA) was performed and the model in Equation 4 was used.

$$\text{Y}_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \qquad (4)$$

Where Y_{ij} is the observed response variable in the *ijth* factors; μ is the overall (grand) mean; α_i and β_j are the main effects of the factors farmer's field characteristics and treatments, respectively; $(\alpha\beta)_{ij}$ is the two-way (first order) interactions between the factors; εij is the random error associated with the observation of response variable in the *ijth* factors.

3 Results and Discussion

3.1 Fertility status of the selected fields in study area

3.1.1 Soil pH

Table 3 shows the pH range of the soils within the research area, which was 6.48 for slightly acidic soils and 7.7 for slightly alkaline soils. The native P content and pH of the soil have an impact on how well phosphate-solubilizing microorganisms work (Wakelin, 2007).

The solubilization of phosphates in soil is facilitated by microbial secretion of low molecular weight organic acids, which alters pH and causes phosphates to become soluble (Chen et al., 2006). Due to anion exchange, these organic acids have the ability to dissolve phosphates or chelate the Ca, Fe, or Al ions that are connected to the phosphates (Gyaneshwar et al., 2002). The pH of the soils in the fields under investigation does not support Minjingu PR solubilization for P release for plant uptake. In this regard, the use of solubilizing bacteria is an important alternative to enhance plant P nutrition (Gyaneshwar *et al*., 2002; van der Heijden *at el*., 2008).

Table 4: **Levels of some chemical properties and their ratings for the studied soils in selected fields in Kongwa district**

VILLAGE	**Farm No.**	**Soil pH_{H2O}**	**TN**	**OC**	**Ext. P (Olsen)**	**S**	**Zn**	**Ca**	**Mg**	**K**
			(%)		**(mg kg^{-1})**			**(cmol$_{(+)}$ kg^{-1})**		
NGHUMBI	1	7.05	0.15*l*	1.11*l*	38.61*h*	10.33*m*	1.98*m*	9.14*h*	3.41*h*	0.25m
	2	7.06	0.09*vl*	1.11*l*	53.51*h*	16.72*m*	3.74*h*	8.76*h*	3.40*h*	0.29*m*
	3	7.1	0.07*vl*	0.74*l*	29.86*h*	17.41*m*	1.91*m*	5.21*h*	2.38*m*	0.33*m*
	4	6.69	0.11*l*	1.26*m*	19.79*l*	13.07*m*	1.78*m*	10.04h	4.06*h*	0.32*m*
	5	6.99	0.05*vl*	0.59*vl*	22.09*m*	21.73*h*	3.86*h*	6.92*h*	3.05*h*	0.21*l*
MLALI	6	7.22	0.02*vl*	0.30*vl*	11.11*l*	21.31*h*	0.94*l*	2.47*m*	1.16*m*	0.24*l*
	7	7.63	0.04*vl*	0.63*l*	9.19*l*	14.43*m*	0.82*l*	5.29*h*	1.23*m*	0.16*l*

Key: M= moderate, h= high, vl= very low, vh = very high, l = low, exch. Ca = exchangeable Ca, ext. P = extractable phosphorus, TN = total nitrogen (Nhunda et al 2024).

3.1.2 Available phosphorus

According to Landon (1991), the results demonstrated that 54% of the chosen fields had sufficient available P, while 46% of the fields had insufficient available P (Table 4). Low P in some fields may result from precipitation by high Cameasured in the examined soils, or it may be related to intrinsic low P in the parent material. The primary determinant of phosphate concentration in the soil's liquid phase is the amount of calcium present in the soil solution (Gyaneshwar et al., 2002).

Microorganisms are essential to the soil P cycle and are involved in the mediation of P availability (Kannapiran and Ravindran, 2012; Turan et al., 2006). According to Adesemoye and Kloepper (2009), phosphate-solubilizing microorganisms can increase crop uptake and production by solubilizing inaccessible soil P. Numerous studies have shown that adding P-solubilizing bacteria or fungi to soil can increase its availability (Chenet al., 2006; Adesemoye and Kloepper, 2009). Numerous autotrophic and heterotrophic soil microorganisms have been found to solubilize mineral phosphorus and to contribute to the mobilization of soil P in forms that are soluble for plants (Chen et al., 2006).

Sumner and Farina (1986) reported that maize responded favorably to the combination of plant-available soil P and N that was applied to the crop. While Ca and Mg were sufficient in all of the soils, the exchangeable K in the soils of the fields under study ranged from low (0.16 cmol(+) kg-1) to medium (0.32 cmol(+) kg-1) (Table 4).

3.1.3 Limiting nutrients in the soils of experimental fields

Table 5 presents the findings of the categorization of limiting nutrients in the soils of the tested areas. The nutrients were categorized and rated based on their distinct chemical characteristics, as listed in Table 4. The limiting nutrients in the soils of the experimental fields were found to be N, P, K, and Zn. All soils were lacking in nitrogen (N), which was fixed by adding fertilizer that contained N (Yara Amidas). The most frequent food crop grown by smallholder farmers in the study area is maize, but inadequate soil fertility—which results from little to no external nutrient inputs—has prevented maize from producing at its maximum yield.

Table 5: Limiting nutrients in each of the selected fields in the studied area in Kongwa district

Village	**Owner**	**Soil pH_{H2O}**	**Limiting nutrients**
Nghumbi	1	7.05	N
	2	7.06	N
	3	7.1	N
	4	6.69	N
	5	6.99	N and K
Mlali	6	7.22	N, P, Zn and K
	7	7.63	N, P, Zn and K

4 Maize Performance in the Study fields

4.1 Effect of field characteristics

In this section, the performance of maize was evaluated according to the specific field selection parameters, like the pH of the soil and the limiting nutrients that were found in each field. ANOVA was used to assess the P concentration, P absorption, P usage efficiency, biological productivity, and grain yield across fields (Table 6 and 7). Table 3.4 and 3.5 show that the farmer's field features significantly affected grain, biomass production, and P concentrations at a p-value of less than 0.001, while the primary treatment effect is insignificant at a p-value of less than 0.001, according to the ANOVA table.

Table 6: Analysis of variance (ANOVA) of P concentration, total P uptake, and P use efficiency in maize as affected by farmer's field characteristics, treatments, and their interactions in Kongwa district

Source of d.f variation		P concentration				Total P uptake				P use efficiency			
		s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Replication	2	0.0516	0.0258	4.31		68.79	34.39	1.92		95550	47775	6.31	
Farmer	6	0.1016	0.0169	2.83	0.059	1800.46	300.08	16.77	<0.001	300204	50034	6.61	0.003
Residual	12	0.0717	0.0060	0.85		214.68	17.89	1.11		90849	7571	0.78	
Treatment	5	0.0140	0.0028	0.4	0.848	88.22	17.64	1.09	0.373	21965	4393	0.45	0.811
Farmer×Treatment	30	0.0927	0.0031	0.44	0.993	302.17	10.07	0.62	0.924	201465	6715	0.69	0.869
Residual	70	0.49	0.007			1131.86	16.17			681168	9731		
Total	125	0.82158				3606.18				1391202			

Key: d.f. =degrees of freedom; s.s. = sum of squares; m.s. = mean sum of squares; v.r. = variance; F pr. = test-F probability

Table 7: Analysis of variance (ANOVA) of biological yield and grain yield in maize as affected by farmer's field characteristics, treatments, and their interactions in Kongwa district

Source of variation	d.f.	Measured variables in maize and statistical parameters								
		Biological yield					Maize grain yield			
		s.s.	m.s.	v.r.	F pr.		s.s.	m.s.	v.r.	F pr.
Replication	2	4.513	2.26	1.1			0.15	0.07	0.19	
Farmer	6	218.26	36.38	17.78	<0.001		88.74	14.79	37.18	<0.001
Residual	12	24.56	2.05	1.36			4.77	0.40	0.9	
Treatment	5	3.66	0.73	0.49	0.785		2.40	0.48	1.09	0.375
Farmer×Treatment	30	49.66	1.66	1.1	0.364		13.86	0.46	1.05	0.427
Residual	70	105.39	1.51				30.94	0.44		
Total	125	406.03					140.87			

Key: d.f. =degrees of freedom; s.s. = sum of squares; m.s. = mean sum of squares; v.r. = variance; F pr. = test-F probability

The chosen fields' maize yields were as follows: farm No. 2 > No. 5 > No. 4 > No. 6 > No. 1 = No. 6 > No. 3. According to the above sequence, field No. 2 had the highest yield of maize of all the fields, with a significant difference (P<0.001) from the other fields. This was indicated by the major effect of field features. Field No. 2 produced 4.0 t ha-of grain (Table 7). Given that the soils in field No. 2 only contained one limiting component, N (Table 4), which was also well-corrected, the soil's favorable qualities were most likely the reason of the significantly high yield. The natural phosphorus content of the field was high, at 53.4 mg kg -1. Field No. 5 had the second-highest maize grain production (3.3 t ha-1), with two limiting nutrients present there. N and K are among these nutrients; N was rectified. As shown in Table 3 (Przygocka et al., 2020), a little limitation of K (0.21), which was near to a moderate level, could be the likely cause of the notable lower yield at this field next to No. 2. Grain yields in fields No. 4 (2.6 t ha-1) and No. 6 (2.2 t ha-1) were the next highest yields, after field No. 5. Field No. 6 had four limiting nutrients, namely N, P, K, and Zn, whereas Field No. 4 had just one limiting nutrient, N (Table 4). It is suggested that the primary reason for field No. 6's low grain yield is these limiting minerals. Furthermore, the No. 1 and No. 7 fields had low grain yields (1.8 t ha-1). Field No. 1 contained just one limiting nutrient (N), but field No. 7 had four (N, P, K, and Zn).

The limiting nutrients in No.7 field are thought to be the reasons for low grain yield while in field No.1 would have been affected by bad weather (drought). Field No.3 (1.5 t ha-1) had the lowest grain yield and had a contrasting trend in that yield did not seem to relate to liming nutrients since N was the only inadequate nutrient and was corrected. In this field the reason could presumably be lack of soil moisture caused by drought experienced in the experimental site during vegetative stage in the early January to mid-February and during flowering to grain filling in March (Fig. 2). According to Figure 2, soil moisture stress occurred during all times when evapotranspiration exceeded rainfall. The order of biological/straw yields straw was as follows: No. 2>No. 4>No. 5>No. 6>No. 3>No. 7>No. 1. Similar to the pattern in grain yield, this trend is also reflected in the fields' limiting nutrient sequence and number, with the exception of field No. 3, which is affected by low soil moisture. These results, with the exception of fields Nos. 3 and 5, are in line with the field characteristics classified according to the limiting nutrients. The trend in P uptake results was No.2 ≈ No.4 ≈ No.5 ≈ No.6 ≈ No.3 ≇ No.7 ≇ No.1. The majority of the phosphorus in maize crops is found in the grains, as has been demonstrated and documented. This has an impact on the nutritional content of the grain, protein, and micronutrients (Wafula et el., 2018). According to Wu et al. (2015), the critical concentration of P in maize straw is 0.26% by mass, of which 60 to 80% is in the form of phytate. In maize straw, a P absorption of 15 to 30 kg ha-1 is ideal (Assefa et al., 2021).

Field No. 2's modest increase in P concentration (i.e., 0.27%) is most likely the result of the soil's high native P content (53.5 mg kg-1), which the plants may have absorbed early in the maize plant's growth. This condition was also noted in field No. 5, where the native P content of the soil was adequate (22.1 mg kg-1) for the growth of maize. It was discovered that fields with lower native P concentrations, such as Nos. 6 and No. 7 (9.2 mg kg-1), had low P concentrations of 0.07 to 0.17% and 0.07 to 0.17%, respectively. These results support the findings of Gomez-Munoz et al. (2018), who found that high native P increases grain-based crop yields. Other researchers have also noted comparable outcomes of increased crop yields on soil with high native P (e.g., Mehrvarz, 2008; Krey *et al*., 2013; Saleque*et al*., 2014; Leggett *et al*., 2015; Santana, 2016; Selvi, 2017; Raymond *et al*., 2019).

Apart from the maize grain yield data, there was a significant difference (P = 0.003) in P usage efficiency between the fields, although no discernible trend was seen. These results indicate the heterogeneity in nutrient levels. In this study, PUE ranged from 195.1 to 351 kg kg-1. According to a study by Baligaret al. (2001), PUE ranged extremely high, from 400 to 500 kg kg-1. The favorable conditions in the study by Baligaret al. (2001) included sufficient soil moisture, which facilitated PSB function and ultimately led to strong plant absorption. This resulted in a high PUE. It is evident that the PUE data are quite low when comparing this range to those found in this investigation. Due of the drought that the experimental site experienced, poor dry matter yield is most likely what causes the usually low PUE levels. The dimensionless ratio of harvested P agricultural products (P yield) to the mass of all P inputs into the system during the specified period is known as phosphorus usage efficiency, or PUE (Chowdhury and Zhang, 2021). According to Chen and Graedel (2016), it is also known as the ratio of P input conversion into valuable plant exports, such as harvested crops. As per Baligaret al. (2001), dividing dry matter yield (kg) by nutrient accumulation/uptake (kg) is one way to represent the efficiency of phosphorus consumption in plants. In this study, PUE has been defined as follows. PUE is significant to the crop production system because it serves as a gauge for the agricultural production system's P management status and its effects on environmental preservation and food security.

4.2 Treatments influence on the performance of maize

Data on grain yield, biological yield, P concentration, straw uptake, and use efficiency are shown in Table 8.

Table 8: P concentration, Straw P uptake, and P use efficiency in maize as affected by farmer's field characteristics and treatments in the study sites in Kongwa district.

Farmer's-No.	**Treatments**	**Grain yield**	**Biological yield**	**P concentration**	**Straw P uptake**	**P use efficiency**
		(t ha^{-1})	**(t ha^{-1})**	**(%)**	**(kg ha^{-1})**	**(kg kg^{-1})**
2		4.0a	5.6a	0.12a	10.81 a	246.8bcd
4		2.6c	4.7ab	0.08ab	7.96ab	219.4cd
1		1.8de	1.5e	0.08ab	2.38d	351.8a
3		1.5e	3.0cd	0.10ab	5.18bcd	195.1d
5		3.3b	4.0bc	0.09ab	7.21abc	272.1bc
7		1.8de	2.2de	0.11a	4.03cd	294.8ab
6		2.2cd	3.4c	0.07b	5.48bcd	296.1ab
S.E.D.		0.22	0.477	0.011	1.351	29
P- value		<0.001	<0.001	0.059	<0.001	0.003
	P_0M_0	2.3a	3.5a	0.10a	5.82a	256.4a
	$P_{20}M_0$	2.4a	3.4a	0.07a	9.85a	280.6a
	P_0M_x	2.7a	3.6a	0.09a	6.59a	267.5a
	$P_{20}M_x$	2.4a	3.3a	0.07a	5.48a	271.5a
	$P_{40}M_x$	2.5a	3.8a	0.08a	7.05a	247a
	$P_{60}M_x$	2.4a	3.4a	0.09a	5.78a	285.3a
	S.E.D.	0.2037	0.379	0.011	1.251	30.44
	P- value	0.441	0.785	0.848	0.373	0.811

Key: S.E.D. = Standard errors of differences of means. *Means in each column bearing different letter(s) differ significantly at 5% error rate; otherwise, are not statistically different.*

In this investigation, the experimental treatment combinations involved applying MPR at varying rates in conjunction with the PSB inoculum. The primary impact of the treatments was found to be negligible across all sites. The first possible explanation is that the study site experienced a drought that started three weeks after emergence and lasted for approximately 35 days in January and February, which resulted in low soil moisture levels, which prevented the P from MPR from dissolving properly (Fig. 2). Second, because of the low soil moisture content, using PSB as an inoculum did not significantly aid in the solubilization of P from MPR. Low soil moisture affects grain yield and total grain content because it decreases PSB activity and P diffusion in the soil and from the soil to plant roots (Frossard et al., 2000). In a field experiencing such a severe drought during the vegetative stage, inoculum sown into the soil would not be able to survive. According to Schutz (2018), in sufficient soil moisture, phosphate solubilizing bacteria have a stronger effect when administered P fertilizer at rates ranging between 40 and 60 P kg P ha-1.

Table 9: Data for grain yield, biological yield, P concentrations, P uptake and P use efficiency in maize as affected by the interactions between farmer's field characteristics and treatments

Farmer's-No.	**Treatments**	**Grain yield**	**Biological yield**	**P concentration**	**Straw P uptake**	**P use efficiency**
		(t ha^{-1})	**(t ha^{-1})**	**(%)**	**(kg ha^{-1})**	**(kg kg^{-1})**
3	P_0M_0	1.11	2.9f-m	0.13ab	6.23f-j	179.2bcd
3	$P_{20}M_0$	1.4jkl	2.6g-m	0.13ab	6.7f-j	211.2bcd
3	P_0M_x	1.8g-l	3.4c-m	0.17ab	8.1e-j	218bcd
3	$P_{20}M_x$	1.4jkl	3.2d-m	0.13ab	9.33c-j	149.3d
3	$P_{40}M_x$	1.9f-l	3.0f-m	0.13ab	7.93e-j	247.5bcd
3	$P_{60}M_x$	1.3kl	3.1e-m	0.10ab	8e-j	165.7cd
1	P_0M_0	1.4jkl	1.1m	0.17ab	4.17j	326.2a-d
1	$P_{20}M_0$	1.9f-l	1.6lm	0.13ab	5.33hij	460.8a
1	P_0M_x	1.7g-l	1.5lm	0.13ab	4.97ij	335.5a-d
1	$P_{20}M_x$	1.6h-l	1.4m	0.17ab	5.3hij	293.4a-d
1	$P_{40}M_x$	2.6c-k	2.2j-m	0.17ab	7.57e-j	358.2abc
1	$P_{60}M_x$	1.4jkl	1.2m	0.13ab	4.17j	337a-d
4	P_0M_0	2.9c-h	4.6a-j	0.13ab	12.93a-i	235.1bcd
4	$P_{20}M_0$	2.1e-l	4.2b-k	0.17ab	10.8b-j	195.9bcd
4	P_0M_x	2.8c-i	5.3a-f	0.17ab	14.07a-g	202.3bcd
4	$P_{20}M_x$	2.9c-h	4.7a-i	0.13ab	11.7a-j	263.4bcd
4	$P_{40}M_x$	2.4d-l	5.0a-h	0.20ab	11.73a-j	226.4bcd
4	$P_{60}M_x$	2.7c-j	4.6a-j	0.17ab	13.73a-g	193.2bcd
5	P_0M_0	3.0b-g	4.2b-k	0.20ab	14.4a-f	215.1bcd
5	$P_{20}M_0$	3.2b-f	3.6b-m	0.17ab	12a-j	293.2a-d
5	P_0M_x	3.9abc	4.8a-i	0.20ab	14.93a-e	261.3bcd
5	$P_{20}M_x$	3.4a-e	3.3c-m	0.13ab	10.27b-j	329.4a-d
5	$P_{40}M_x$	2.4d-l	4.2b-k	0.17ab	13.63a-g	201.1bcd
5	$P_{60}M_x$	4.2ab	3.9b-l	0.17ab	13.27a-h	332.7a-d
2	P_0M_0	4.2ab	6.0ab	0.20ab	17.37abc	248.6bcd
2	$P_{20}M_0$	3.6a-d	4.5a-j	0.20ab	13.2a-h	307.7a-d
2	P_0M_x	4.4a	5.1a-g	0.27a	18.13ab	257bcd
2	$P_{20}M_x$	3.7abc	5.7abc	0.20ab	16.93a-d	225.1bcd
2	$P_{40}M_x$	3.9abc	5.6a-e	0.23ab	19.63a	213bcd
2	$P_{60}M_x$	3.8abc	6.8a	0.20ab	17.23abc	229.3bcd
	S.E.D.	0.5389	1.031	0.06748	3.309	79.04
	P- value	0.427	0.364	0.993	0.924	0.869

Key: S.E.D. = Standard errors of differences of means. *Means in each column bearing different letter(s) differ significantly at 5% error rate; otherwise, are not statistically different.*

Table 10: Data for grain and biological yield, P concentration, straw P uptake, P use efficiency in maize as affected by the interactions between farmer's field characteristics and treatments

Farmer's-No	Treatments	Grain yield	Biomass yield	P concentration	Straw P uptake	P use efficiency
		(t ha^{-1})	(t ha^{-1})	(%)	(kg ha^{-1})	(kg kg^{-1})
6	P_0M_0	1.9f-l	2.3i-m	0.13ab	6.1g-j	317.1a-d
6	$P_{20}M_0$	2.4d-l	4.1b-k	0.13ab	11.87a-j	220.2bcd
6	P_0M_x	2.3e-l	2.5h-m	0.10ab	7.37e-j	318.7a-d
6	$P_{20}M_x$	2.1e-l	3.3c-m	0.07b	7.17e-j	317.3a-d
6	$P_{40}M_x$	2.7c-j	5.6a-d	0.13ab	13.77a-g	233.7bcd
6	$P_{60}M_x$	2.0f-l	2.6g-m	0.17ab	8.27e-j	369.9ab
7	P_0M_0	1.6h-l	3.4c-m	0.10ab	7.27e-j	273.5a-d
7	$P_{20}M_0$	2.1e-l	3.0f-m	0.13ab	9.07d-j	275a-d
7	P_0M_x	2.2e-l	2.4i-m	0.17ab	10.67b-j	279.9a-d
7	$P_{20}M_x$	1.7h-l	1.6lm	0.17ab	5.3hij	322.4a-d
7	$P_{40}M_x$	1.5i-l	1.2m	0.17ab	7.9e-j	249bcd
7	$P_{60}M_x$	1.7g-l	1.8klm	0.07b	4.83ij	369.2ab
	S.E.D.	0.5389	1.031	0.067	3.309	79.04
	P- value	0.427	0.364	0.993	0.924	0.869

Key: S.E.D. = Standard errors of differences of means. *Means in each column bearing different letter(s) differ significantly at 5% error rate; otherwise, are not statistically different.*

Grain yields were marginally greater in field No. 2 with P0Mx (4.4 t ha-1) treatments than in P40Mx (3.9 t ha-1) treatments, but there was no significant (P =0.427) interaction effect between field features and treatments on the measured variables (Table 9 and 10). Based on this discovery and in accordance with earlier findings documented in the main effect of treatment, natural P, rather than the given MPR and inoculant combinations, was the primary source of P in the crops. These results imply that the nutritional status of the soil, particularly P, N, and K, affects maize productivity in the study area. An intriguing discovery revealed by interaction effects is that soil and the quantity of P released or supplied to the soil determine how maize responds to native P inputs in the study area. These results are consistent with the findings of Frossard et al. (2000), who observed that a variety of factors, including soil conditions, influence crop performance.

5 Conclusions and Recommendations

In every field where maize crop production systems were evaluated, nitrogen was the limiting nutrient element. In addition to N, other limiting nutrients were noted in fields No. 5 and No. 6, which had limited potassium (K) and P, respectively, and field No. 7, which had limited P, K, and Zn. With the highest grain production, biological yield, and total P uptake among all other fields, field No. 2's maize performance was statistically the best, according to the major effect of the field's features. In addition, there were notable variations in P usage efficiency among the fields, which could be attributed to variations in nutrient levels. The primary outcome of the treatments showed that using P or inoculants independently did not increase grain yield in a way that was encouraging. Grain yields in field No. 2 were significantly greater than in other fields because of its high native P in soils, even though there were no significant interaction effects of field features and treatment combination on the measured variables in maize. These results imply that native P and soil nutrient status, particularly N and K, affect maize productivity in the studied area.

Before the technique is suggested for farmers to use, we advise doing additional field trials spanning multiple seasons to determine the significance of solubilizing bacteria in boosting P availability from MPR for increase of maize yield.

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