OriginalResearchArticle

EFFECTIVENESSOFPHOSPHORUSSOLUBILIZINGBACTERIAONENHANCINGPHOSPHORUS AVAILABILITYFROMMINJINGUPHOSPHATEROCKTOMAIZEINSLIGHTLYACIDTO NEUTRALSOILS

Abstract

Theaimofthisone-yearfieldstudywastoevaluatetheimpactofphosphorussolubilizing bacteria(PSB)onincreasingtheavailabilityofphosphoruslockedupininsolubleMinjingu phosphaterockforthemaizecrop(ZeamaysL.)inhighsoilpH.Thestudywascarriedout duringonewetseasoninNghumbiandMlalivillagesinKongwaDistrictintheDodomaRegion, Tanzania.BasedonthepHoftheirsoilandthelimitingnutrients,twofarmsfromMlalivillage andfivefromNghumbivillagewerechosenatrandomforfieldtrials.Todeterminethe fertilitystatus,compositesoilsampleswerecollectedfromthechosenfarmsandexamined inalab.TargettreatmentsincludedtheapplicationofPSBinoculumincombinationwith variousratesofMinjinguphosphaterock(MPR)(0,20,30,40,and60KgPha-1)asabasal fertilizer,placedbeneathmaizeseedandcoveredwithathinlayerofsoil.Usingafully randomised block design,thetreatmentsweresetupthree times.Inadequatelevelsof N,P, K,andZnwerefoundintheresearcharea'ssoilsamples.Resultsindicatedthemaineffectof fields’characteristicsfromfieldNo.2hadthehighestyieldtootherfieldswithsignificantly (*P*<0.001)highestgrainyieldbeing4.4tha^{-1},biologicalyieldof5.6tha^{-1},andStrawPuptake of19.63kgha^{-1}.UsingPoraninoculant(Mx)producedanegligibleyieldofgrainandstraw, accordingtothemajoreffectoftreatments.Forthestudiedvariables,noneofthetreatments showedanysignificant(P=0.427)interactioneffects.Anintriguingrevelationthatthestudy's maizeresponsetonativePisprovidedbyinteractioneffectsareaisafactorofsoilandamount ofPreleasedtothesoil.WerecommendmoreresearchonPSB formorethanoneseason in highsoilpHbeforeascertainingthetechnologytofarmers.

Keywords: Bio-fertilizer;croppingsystems;Foodcrops;Soilfertility;Tanzania.

1Introduction

Alongwithothernutritionalelements,phosphorus(P)isthemacronutrientthatoften restrictsplantgrowthandthefinaloutput.Asaplantages,phosphorusthathasbeen absorbedismovedtoitsfruitingsections,wheretheproductionofseedsnecessitatesa significantenergyexpenditure.Soilphosphorusdeficitsaffectnormalcropmaturityaswell asseeddevelopment.ThemostcommonnutrientdeficiencyintropicalAfricansoilsis phosphorus,whichsignificantlyrestrictsTanzania'sabilitytoproducemaize.Accordingto Nhundaetal. (2024), low-accessPisaprobleminKongwadistrict,asevidencedby thesoil's acidicandalkalineconditions.LowPintheparentmaterialandhighPfixationbyironand aluminumoxidesinacidarethecausesoflow-soilP(Silesh*etal.,*2022)andprecipitationby calciuminalkalinesoils(Adnan*etal*.,2017).

Sincethe1960s,Tanzaniahaspaidcloseattentiontotheuseofphosphaterock(PR),suchas Minjinguphosphaterock(MPR),asanalternativePsource(Anderson,1993;Ikerraetal., 1994;Szilas,2002).PreviousresearchfindingsindicatedthatMPR'sresidualeffectmadeit superiortosubsequentcropsinthefieldaftertheoriginalapplication(Ikerraetal.,2007).The prolongedandcontinualgradualreleaseofPfromMPRis thecause ofthehighresidualand long-lastingeffects.Numerousstudieshavedocumented PR'scapacitytoreleaseP,butlittle isknownabouthowhigh/alkalinepHinfluencesthematerial'sabilitytodissolveinsoil.

DuetothelackofsolubilizationrequiredtoliberatePforcropuse,PRisdifficulttousefor cropproductioninneutral(pH6.6–7.3)andalkaline(pH>7.3)soils.AssoilpHclimbsto6.2, PRsolubilizesswiftlyatpHrangesof4.9to5.5.AccordingtoAnderson*etal*.(2018),PR becomescompletelyinsolubleatpHvalueshigherthan6.1.BolanandHedley(1990) employedthreeformsofPR:JordanPR(JPR),NorthCarolinaPR(NCPR),andNauruPR(NPR). ThedegreeofPRdissolvingateachpHwasdeterminedtofollow thefollowingorder,based onthedecreasingorderofthechemicalreactivities:AssoonasthepHdroppedbelowsix, fromNCPR>JPR>NPR.5to3.9,thedissolutionofPRsincreasedfrom29.3%to83.5%,from 18.2%to78.9%,andfrom12.5%to60.3%forNCPR,JPR,andNPR,respectively.

IncontrastasthepHdecreased from6.5to3.9,theproportionalofdissolvedPextractedby 0.5M$NaHCO_3$decreasedfrom38%to 5%andtheproportionofPtakenupbyryegrassplant decreasedfrom46%to7%(BalonandHedley,1990).ThedecreaseinplantavailableP correspondstoanincreaseinadsorptionofinorganicPinlowpH(BalonandHedley,1990). BalonandHedley(1990)furthernotedthatanincreaseinpHwasassociatedindecreased degreeofPRdissolution.Warren*etal*.(2009)reportedthatdissolutionofPfromPRwas insignificantatpH>6.1whilecitingoutthe causesbeingpHinthemediaandPsorption.

Itisnecessarytoinvestigateauniquemechanisminordertoreleasethelocked-upPinthe insolublePRwhen it isappliedathigh soil pH.Ithasbeenreported that phosphorus solubilisingbacteriaconvertinsolubletosolublePfromPRbyreleasinglow-weightmolecular organicacidssuchasacetic,formic, propionic,lactic,glycolic,andfomicacids(Zaworotko*et al*.,2019).Carboxylandhydroxylgroupsfromorganicacidsarecapableofchelatingwith cationsboundtophosphatetherebyconvertingitintosolubleforms(Zaworotko*etal*.,2019). Additionally,thebacteriaproduceacidityb yevolvingcarbondioxide(CO2),whichcauses calciumphosphatestobecomesoluble(Yousefietal.,2011).Ithasbeendemonstratedthat insoilswithhighpHvalues(>6.2),phosphorus-solubilizingbacteriaimprovePavailability, hencepromotingcropgrowth(BhattacharyyaandJha,2012).

Accordingtoreports,inoculatingPSBintosoilcontaminatedwithmetalsincreasedmaize production(Jiangetal.,2008).Linuetal.(2009)discoveredthenodulation,root,andshoot biomassoftheB-inoculatedmaizeandcowpeaplants.*Comparedto the controlgroup,there werenotablymoreCepacta.*WhilethebenefitsofbacteriainraisingPavailabilityfromPR arewellestablishedinacidicsoils,theyhavenotbeenconsistentlyshowninTanzanian alkaline soilstudies (Zaidietal.,2009). Thereis adearthofinformation on highpH soils,and theoutcomesofthelittlethatisavailableareevasiveorunclear.Thestudyaimstoincrease 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).

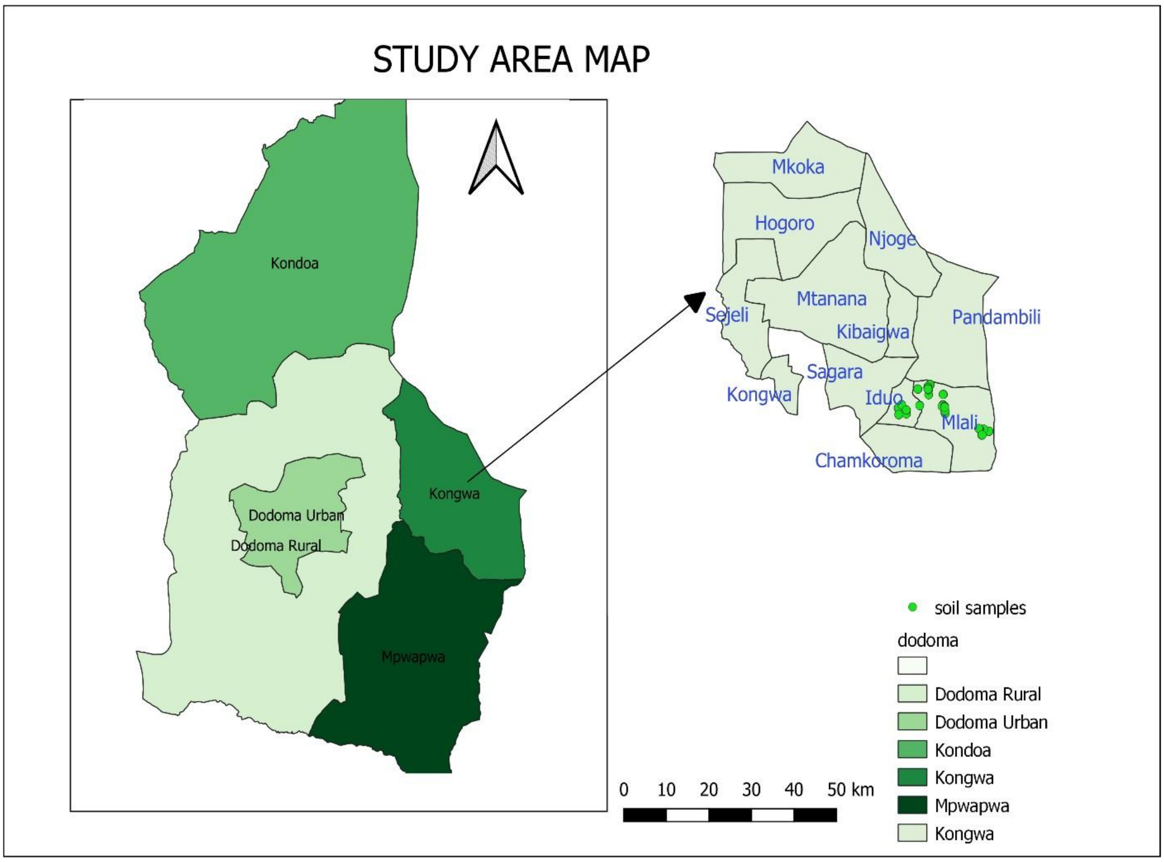

Figure 1: Map of Dodoma region showing study district and villages in which experiment was conducted

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.

Whenmaizeplants wereintheexperimentalfields,therewas no linear(polynomial)dropin temperatureorrainfall.TheclosestexperimentallocationusedbyCasper(2002)tocollect evapotranspirationdataprovidedtheevapotranspiration data.

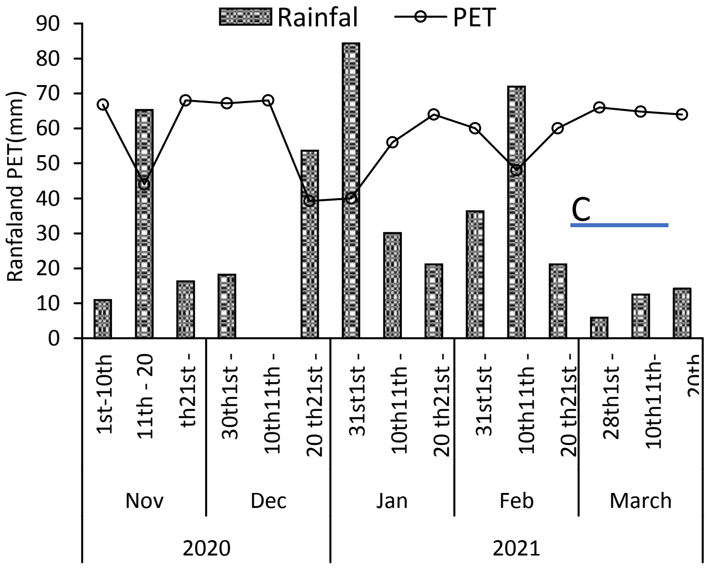

Figure2: *Trendsofrainfall(mm)andevapotranspirationinthestudyareaduringperiodof experimentationwithmaizecrop– Kongwadistrict.L=showstheplanting date,B=isthe droughtperiodduringvegetativegrowth,C= droughtperiodduringfloweringandgrain filling*

Table2:IdentityofisolatedPR-solubilizingspeciesbasedonnucleotidedatabaseon AmericanNationalInstituteofHealth(NIH)NCBIgeneticdatabase(GenBnk)(source:SUA soillaboratorypublishedbyKwaslema,2021).

Isolate	**Species**	**Accession number**	**Nucleotide identity**	**Country**	**Sourcerhizosphere**
Fg1	*Fusarium proliferatum*	MZ497514	100	Tanzania	Maize
Mk10	*Burkholderiasp*	MZ502221	99.9	Tanzania	Maize
NA19a	*Klebsiellasp*	MZ502673	99.9	Tanzania	Maize
Klm3	*Burkholderiasp*	MZ502220	99.9	Tanzania	Maize
MbMz1	*Klebsiellasp*	MZ502668	99.8	Tanzania	Maize
Sl-Sp1	*Klebsiellasp*	MZ502674	99.8	Tanzania	Sweet potato
NA4a	*Unidentified*			Tanzania	Irishpotato
NA4b	*Klebsiellasp*	MZ502671	99.8	Tanzania	Irishpotato
SUApp3	*Klebsiellasp*	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

2.3Experimentaldesign,treatment,andfieldexperimentation

Sevenfields(twoatMlaliandfiveatNghumbi)withthedesiredsoilpHinthestudyareawere selected.Trialsusingmaizeasatestcropinsevenselectedfieldswereestablished.The treatmentcombinationswerePSBinoculumco-appliedwithMPRatdifferentrates,asshown in table2.

Table3.Treatmentcombinationsusedinastudy

S/N	Treatment	Treatmentsymbol	Description
1	T1	P_0M_0	treatmentcontrol
2	T2	$P_{30}M_0$	MPRat 30 kgha^{-1}
3	T3	P_0M_x	OnlyPSB
4	T4	$P_{20}M_x$	MPRat20 kgha^{-1} with PSB
5	T5	$P_{40}M_x$	MPRat 40kgPha^{-1} withPSB
6	T6	$P_{60}M_x$	MPRat 60kgPha^{-1} withPSB

Therewerethreereplicationsofthetreatments,foratotalof eighteen plots. Usingmaize as thetestcropandthreereplicationsorblocksoftreatmentsineachofthesevenfields,the studyusedarandomizedcompleteblockdesign(RCBD).Everytestplotmeasured4min lengthand3minbreadth,or12m^2.BetweenDecember25thand30th,twomaizeseeds (varietySituka)wereplantedineachhole.Asaresult,therewerefourrowsandthirteenholes inarow,witha90cmgapbetweenrowsanda30cmgapwithinrows.ApplyingthePSB inoculumundermaize seed,variousratesof Pfrom MPR(0,20,30,40, and 60 kgha-1)were combinedwithitasabasalfertilizerandaddingalittlelayerofsoilontop.Everyplantinghole received5mLofsolution containingtheinoculum.LimitingnutrientslikeNand Swerefixed byusingYaraAmidas,whichwasdividedintotwodressings:abasaldressingandatop dressing(N40%andS5.5%).

2.4Datacollection

2.4.1Laboratorysoilanalysis

Beforefield selectionandthecommencementoffieldtrials,thesoilswereassessedfortotal nitrogenusingthemicro-Kjedahlmethod(BremnerandMulvaney,1982).AvailablePwas extractedusingtheBray-1method(1982),anditscolorwasdeterminedusinga spectrophotometerusingthemolybdenumbluemethod(MurphyandRiley,1962). ExchangeableKwasfoundinammoniumacetatefiltratesusingaflamephotometer.The samefiltrateincludedexchangeableCaandMg,asdeterminedbyatomicadsorption 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.

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

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.

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

Where Yij 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.

3ResultsandDiscussion

3.1Fertilitystatusoftheselected fieldsinstudyarea

3.1.1 Soil pH

Table3showsthepHrangeofthesoilswithintheresearcharea,whichwas6.48forslightly acidicsoilsand7.7forslightlyalkalinesoils.ThenativePcontentandpHofthesoilhavean impactonhowwellphosphate-solubilizingmicroorganismswork(Wakelin,2007).

Thesolubilizationofphosphatesinsoilisfacilitatedbymicrobialsecretionoflowmolecular weightorganicacids,which alterspHandcausesphosphatestobecomesoluble(Chenet al., 2006).Dueto anionexchange,these organic acids have theability to dissolvephosphatesor chelatetheCa,Fe,orAlionsthatareconnectedtothephosphates(Gyaneshwaretal.,2002). ThepHofthesoilsinthefieldsunderinvestigationdoesnotsupportMinjinguPR solubilizationforPreleaseforplantuptake.Inthisregard,theuseofsolubilizingbacteriais animportantalternativetoenhanceplantPnutrition(Gyaneshwar*etal*.,2002;vander Heijden*at el*.,2008).

Table4: **Levelsofsomechemicalpropertiesandtheirratingsforthestudiedsoilsin selectedfieldsinKongwadistrict**

VILLAGE	**Farm No.**	**Soil pH$_{H2O}$**	**TN**	**OC**	**Ext. P(Olsen)**	**S**	**Zn**	**Ca**	**Mg**	**K**
			(%)		**(mgkg^{-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=verylow,vh= veryhigh,l=low,exch.Ca=exchangeableCa, ext.P=extractablephosphorus,TN =totalnitrogen(Nhundaetal2024).

3.1.2Availablephosphorus

AccordingtoLandon(1991),theresultsdemonstratedthat54%ofthechosenfieldshad sufficientavailableP,while46%ofthefieldshadinsufficientavailableP(Table4).LowPin somefieldsmayresultfromprecipitationbyhighCameasuredintheexaminedsoils,oritmay berelatedtointrinsiclowPintheparentmaterial.Theprimarydeterminantofphosphate concentrationinthesoil'sliquidphaseistheamountofcalciumpresentinthesoilsolution (Gyaneshwaretal.,2002).

MicroorganismsareessentialtothesoilPcycleandareinvolvedinthemediationofP availability(KannapiranandRavindran,2012;Turanetal.,2006).AccordingtoAdesemoye andKloepper(2009),phosphate-solubilizingmicroorganismscanincreasecropuptakeand productionbysolubilizinginaccessiblesoilP.NumerousstudieshaveshownthataddingP-solubilizingbacteriaorfungitosoilcanincreaseits availability(Chenetal.,2006;Adesemoye andKloepper,2009).Numerousautotrophicandheterotrophicsoilmicroorganismshave beenfoundtosolubilizemineralphosphorusandtocontributetothemobilizationofsoilPin formsthataresolubleforplants(Chenetal.,2006).

SumnerandFarina(1986)reportedthatmaizerespondedfavorablytothecombinationof plant-availablesoilPandNthatwasappliedtothecrop. WhileCaandMg weresufficientin allofthesoils,theexchangeableKinthesoilsofthefieldsunderstudyrangedfromlow(0.16 cmol(+)kg-1)tomedium(0.32cmol(+)kg-1)(Table4).

3.1.3Limitingnutrientsinthesoilsofexperimentalfields

Table5presentsthefindingsofthecategorizationoflimitingnutrientsinthesoilsofthe testedareas.Thenutrientswerecategorizedandratedbasedontheirdistinctchemical characteristics,aslistedinTable4.Thelimitingnutrientsinthesoilsoftheexperimentalfields werefoundtobeN,P,K,andZn.Allsoilswerelackinginnitrogen(N),whichwasfixedby addingfertilizerthatcontainedN(YaraAmidas).Themostfrequentfoodcropgrownby smallholderfarmersinthestudyareaismaize,butinadequatesoilfertility—whichresults fromlittletonoexternalnutrientinputs—haspreventedmaizefromproducingatits maximum yield.

Table5:LimitingnutrientsineachoftheselectedfieldsinthestudiedareainKongwa 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	Nand K
Mlali	6	7.22	N,P,ZnandK
	7	7.63	N,P,ZnandK

4MaizePerformanceintheStudyfields

4.1Effectoffieldcharacteristics

Inthissection,theperformanceofmaizewasevaluatedaccordingtothespecificfield selectionparameters,likethepHofthesoilandthelimitingnutrientsthatwerefoundineach field.ANOVAwasusedtoassessthePconcentration,Pabsorption,Pusageefficiency, biologicalproductivity,andgrainyieldacrossfields(Table6and7).Table3.4and3.5show thatthefarmer'sfieldfeaturessignificantlyaffectedgrain,biomassproduction,andP concentrationsatap-valueoflessthan0.001,whiletheprimarytreatmenteffectis insignificantatap-valueoflessthan0.001,accordingtotheANOVAtable.

Table6:Analysisofvariance(ANOVA)of Pconcentration,totalPuptake,andPuseefficiencyinmaizeasaffectedbyfarmer’sfieldcharacteristics, treatments,andtheirinteractions inKongwadistrict

Sourceofd.fvariation		**Pconcentration**				**TotalPuptake**				**Puseefficiency**			
		s.s.	**m.s.**	**v.r.**	**Fpr.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**
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.=degreesoffreedom; s.s.=sumofsquares; m.s.= meansumofsquares; v.r.= variance;Fpr.=test-Fprobability

Table 7: Analysis of variance (ANOVA) of biological yield and grain yield in maize as affected by farmer’s field characteristics, treatments,and theirinteractionsinKongwadistrict

Sourceofvariation	**d.f.**	**Measuredvariablesinmaize andstatisticalparameters**								
		Biologicalyield					**Maizegrainyield**			
		s.s.	**m.s.**	**v.r.**	**Fpr.**		**s.s.**	**m.s.**	**v.r.**	**Fpr.**
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.=degreesoffreedom; s.s.=sumofsquares; m.s.= meansumofsquares; v.r.= variance;Fpr.=test-Fprobability

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 ofall the fields, with a significant difference (P<0.001) from the other fields. This was indicatedby the major effect of field features. Field No. 2 produced 4.0 t ha-of grain (Table 7). Giventhat the soils in field No. 2 only contained one limiting component, N (Table 4), which wasalsowell-corrected,thesoil'sfavorablequalitiesweremostlikelythereasonofthesignificantly highyield.Thenaturalphosphorus contentof thefield washigh,at 53.4mgkg-1. Field No. 5 had the second-highest maize grain production (3.3 t ha-1), with two limitingnutrientspresentthere.NandKareamongthesenutrients;Nwasrectified.AsshowninTable3 (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 infields 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 justone limiting nutrient, N (Table 4). It is suggested that the primary reason for field No. 6's lowgrain yield is these limiting minerals. Furthermore, the No. 1 and No. 7 fields had low grainyields(1.8tha-1).FieldNo.1containedjustonelimitingnutrient(N),butfieldNo.7hadfour(N,P,K,andZn).

The limiting nutrients in No.7 field are thought to be the reasons for low grain yield while infieldNo.1wouldhavebeenaffectedbybadweather(drought).FieldNo.3(1.5tha-1)hadthelowest grain yield and had a contrasting trend in that yield did not seem to relate to limingnutrientssinceNwastheonlyinadequatenutrientandwascorrected.InthisfieldthereasoncouldpresumablybelackofsoilmoisturecausedbydroughtexperiencedintheexperimentalsiteduringvegetativestageintheearlyJanuarytomid-Februaryandduringfloweringtograinfilling in March (Fig. 2). According to Figure 2, soil moisture stress occurred during all timeswhen evapotranspiration exceeded rainfall. The order of biological/straw yields straw was asfollows:No.2>No.4>No.5>No.6>No.3>No.7>No.1.Similartothepatterningrainyield,thistrend isalsoreflectedinthefields'limitingnutrientsequenceandnumber,withtheexceptionoffieldNo.3, whichisaffectedbylowsoilmoisture.Theseresults,withtheexceptionoffieldsNos. 3 and 5, are in line with the field characteristics classified according to the limitingnutrients.ThetrendinPuptakeresultswasNo.2≈No.4≈No.5≈No.6≈No.3≆No.7≆No.1.Themajorityofthephosphorusinmaizecropsisfoundinthegrains,ashasbeendemonstrated 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 criticalconcentration of P in maize straw is 0.26% by mass, of which 60 to 80% is in the form ofphytate.Inmaize straw,aP absorptionof15to30 kgha-1 isideal(Assefaetal.,2021).

Field No. 2's modest increase in P concentration (i.e., 0.27%) is most likely the result of thesoil's high native P content (53.5 mg kg-1), which the plants may have absorbed early in themaizeplant'sgrowth.ThisconditionwasalsonotedinfieldNo.5,wherethenativePcontentof the soil was adequate (22.1 mg kg-1) for the growth of maize. It was discovered that fieldswith lower native P concentrations, such as Nos. 6 and No. 7 (9.2 mg kg-1), had low Pconcentrations of 0.07 to 0.17% and 0.07 to 0.17%, respectively. These results support thefindings of Gomez-Munoz et al. (2018), who found that high native P increases grain-basedcropyields.Otherresearchershavealsonotedcomparableoutcomesofincreasedcropyieldsonsoilwithhighnativep(e.g.,Mehrvarz,2008;Krey*etal*.,2013;Saleque*etal*.,2014;Leggett*etal*.,2015;Santana, 2016;Selvi,2017;Raymond *etal*.,2019).

Apartfromthemaizegrainyielddata,therewasasignificantdifference(P=0.003)inPusageefficiency between the fields, although no discernible trend was seen. These results indicatethe 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 kgkg-1. The favorable conditions in the study by Baligaret al. (2001) included sufficient soilmoisture, which facilitated PSB function and ultimately led to strong plant absorption. ThisresultedinahighPUE.ItisevidentthatthePUEdataarequitelowwhencomparingthisrangetothosefoundinthisinvestigation.Dueofthedroughtthattheexperimentalsiteexperienced, poor dry matter yield is most likely what causes the usually low PUE levels. Thedimensionless ratio of harvested P agricultural products (P yield) to the mass of all P inputsinto 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 theratio of P input conversion into valuable plant exports, such as harvested crops. As perBaligaretal.(2001),dividingdrymatteryield(kg)bynutrientaccumulation/uptake(kg)isoneway to represent the efficiency of phosphorus consumption in plants. In this study, PUE hasbeendefinedasfollows.PUEissignificanttothecropproductionsystembecauseitservesasa gauge for the agricultural production system's P management status and its effects onenvironmentalpreservationandfoodsecurity.

4.2Treatmentsinfluenceontheperformanceofmaize

Data on grain yield, biological yield, P concentration, straw uptake, and use efficiency areshown inTable8.

Table8:Pconcentration,StrawPuptake,andPuseefficiencyinmaizeasaffectedbyfarmer'sfieldcharacteristicsandtreatmentsinthestudysitesinKongwadistrict.

Farmer's-No.	Treatments	Grainyield	Biological yield	P concentration	Straw P uptake	P useefficiency
		(tha^{-1})	(tha^{-1})	(%)	(kgha^{-1})	(kgkg^{-1})
2		4.0a	5.6a	0.12a	10.81a	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 bearingdifferent letter(s) differ significantly at 5% error rate; otherwise, are not statisticallydifferent.*

In this investigation, the experimental treatment combinations involved applying MPR atvarying rates in conjunction with the PSB inoculum. The primary impact of the treatmentswas found to be negligible across all sites. The first possible explanation is that the study siteexperiencedadroughtthatstartedthreeweeksafteremergenceandlastedforapproximately 35 days in January and February, which resulted in low soil moisture levels,whichpreventedthePfromMPRfromdissolvingproperly(Fig.2).Second,becauseofthelow soil moisture content, using PSB as an inoculum did not significantly aid in the solubilizationof P from MPR. Low soil moisture affects grain yield and total grain content because itdecreases PSB activity and P diffusion in the soil and from the soil to plant roots (Frossard etal.,2000).Inafieldexperiencingsuchasevereddroughtduringthevegetativestage,inoculumsown into the soil would not be able to survive. According to Schutz (2018), in sufficient soilmoisture,phosphatesolubilizingbacteriahaveastrongereffectwhenadministeredPfertilizer atratesrangingbetween40and60Pkg Pha-1.

Table 9: Data for grain yield, biological yield, P concentrations, P uptake and P useefficiencyinmaizeasaffectedbytheinteractionsbetweenfarmer'sfieldcharacteristicsand treatments

Farmer's-No.	**Treatments**	**Grain yield**	**Biological yield**	**P concentration**	**Straw Puptake**	**P useefficiency**
		(tha^{-1})	**(tha^{-1})**	**(%)**	**(kgha^{-1})**	**(kgkg^{-1})**
3	P_0M_0	1.1l	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 bearingdifferent letter(s) differ significantly at 5% error rate; otherwise, are not statisticallydifferent.*

Table 10: Data for grain and biological yield, P concentration, straw P uptake, P useefficiencyinmaizeasaffectedbytheinteractionsbetweenfarmer'sfieldcharacteristicsand treatments

Farmer's-No	Treatments	Grain yield	Biomass yield	P concentration	Straw P uptake	P useefficiency
		(tha^{-1})	(tha^{-1})	(%)	(kgha^{-1})	(kgkg^{-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 bearingdifferent letter(s) differ significantly at 5% error rate; otherwise, are not statisticallydifferent.*

Grain yields were marginally greater in field No. 2 with P0Mx (4.4 t ha-1) treatments than inP40Mx (3.9 t ha-1) treatments, but there was no significant (P =0.427) interaction effectbetweenfieldfeaturesandtreatmentsonthemeasuredvariables(Table9and10).Basedonthis discovery and in accordance with earlier findings documented in the main effect oftreatment,naturalP,ratherthanthegivenMPRandinoculantcombinations,wastheprimarysourceofPinthecrops.Theseresultsimplythatthenutritionalstatusofthesoil,particularlyP, N, and K, affects maize productivity in the study area. An intriguing discovery revealed byinteractioneffectsisthatsoilandthequantityofPreleasedorsuppliedtothesoildeterminehow maizerespondstonativePinputsinthestudyarea.Theseresultsareconsistentwiththefindings of Frossard et al. (2000), who observed that a variety of factors, including soilconditions,influencecropperformance.

5ConclusionsandRecommendations

Ineveryfieldwheremaizecropproductionsystemswereevaluated,nitrogenwasthelimitingnutrientelement.InadditiontoN,otherlimitingnutrientswerenotedinfieldsNo.5andNo.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 allotherfields,fieldNo.2'smaizeperformancewasstatisticallythebest,accordingtothemajoreffect of the field's features. In addition, there were notable variations in P usage efficiencyamong the fields, which could be attributed to variations in nutrient levels. The primaryoutcomeofthetreatmentsshowedthatusingPorinoculantsindependentlydidnotincreasegrainyieldinawaythatwasencouraging.GrainyieldsinfieldNo.2weresignificantlygreater thaninotherfieldsbecauseofitshighnativePinsoils,eventhoughtherewerenosignificantinteraction effects of field features and treatment combination on the measured variables inmaize. These results imply that native P and soil nutrient status, particularly N and K, affectmaizeproductivity inthestudied area.

Before the technique is suggested for farmers to use, we advise doing additional field trialsspanning multiple seasons to determine the significance of solubilizing bacteria in boosting PavailabilityfromMPR forincreaseofmaizeyield.

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