SOIL FERTILITY ASSESSMENT AND MICROBIAL ENHANCED SOLUBILITY OF MINJINGU PHOSPHATE ROCK IN NEUTRAL TO SLIGHTLY ALKALINE SOILS OF KONGWA DISTRICT

DANIEL MASUMBUKO NHUNDA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE AND LAND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

2023

EXTENDED ABSTRACT

To optimize production of maize and other crops, assessment of soil fertility should be done in agricultural areas from which cite specific fertilizer recommendations will be established. This study was conducted in selected fields of Kongwa district in Dodoma Region to assess the soil fertility status and maximize availability of Phosphate from Minjingu phosphate rock (MPR) for maize production through the use of phosphate solubilizing bacteria (PSB).

The specific objectives of the study were to determine the levels of N, P, K, S, Mg, Ca, Na, Zn, Cu, Fe and Mn in soils and evaluate capability of phosphate solubilizing bacteria (PSB) on enhancing P availability from Minjingu Phosphate Rock (MPR) and evaluate field characteristics in slightly acid to neutral soils.

Assessment of soil fertility status was done by analysing soils from twenty-four maize growing areas of Kongwa district. Composite soil samples of top soils (0 – 20 cm depth) were collected for physical and chemical analysis. Organic carbon was determined by the Walkley-and Black wet oxidation method (Nelson and Sommers, 1982) and total nitrogen (TN) by the micro-Kjeldahl procedure (Loria *et al.*, 2005). Available P was extracted using Bray-1 and Olsen methods of Bray and Kurtz (1945) and measured by Spectrophotometer following colour developed by molybdenum blue method (Murphy and Riley, 1962). Exchangeable bases were extracted by ammonium acetate saturation method (Thomas, 1986) and cation exchange capacity was determined from NH_4^+ saturated soil colloids and displaced using 1 M KCl, then determined by Kjeldahl distillation method for estimation of cation exchange capacity (CEC) of the soil (Robertson and Philip *et al.*, 1999). Extractable sulphur ($SO4^{2-}$S) was extracted using

calcium monophosphate ($Ca(H_2PO_4)_2.H_2O$), then determined by the turbidimetric method as described by Moberg (2001). The EC for soil samples from Kongwa was measured by using EC meter in a 1:2.5 soil: water (or $CaCl_2$ for pH only) extract as described by McLean, (1982).Extractable metallic micronutrients e.g., Cu, Fe, Zn and Mn, were extracted by diethylene triaminepentacetic acid (DTPA) as described by Lindsay and Norvell (1978).

Results indicated that 48% of the sampled fields were sandy clay loam, 26% were sandy loam and the remaining whad a clay or loamy sand textural classes. Soil pH ranged from extremely acid (3.52) to moderately alkaline (7.7), organic carbon ranged from very low to medium (0.19-1.60%) and total N values were very low to low (0.01-015%). Also, results indicated 42% of soils had P deficiency and 16.7% with inadequate S. In addition, 45.8% of the soils had inadequate exchangeable K and exchangeable Mg were very low to high (0.29-4.06cmol$_{(+)}$ kg^{-1}). Exchangeable Ca was low to very high (1.06 to 10.04 cmol$_{(+)}$ kg^{-1}) with favourable base saturation for crop production. The CEC ranged from very low (2.62cmol$_{(+)}$ kg^{-1}) to medium (18.9 cmol$_{(+)}$ kg^{-1}). Extractable micronutrients such as Cu, Fe, and Mn were adequate but Zn was inadequate in 58% of the soils. The study area had poor soil fertility is poor with deficiencies in N, P, K, Zn, Mg, and Ca, hence calling for proper management to improve crop production.

Phosphorus (P) is one of the major growth-limiting macronutrients required for proper plant growth and it is contained within nucleic acids, enzymes, coenzymes, nucleotides, and phospholipids. One of the ways to replenish P in soils is the use of inorganic fertilizers such as Minjingu Phosphate rock. The challenge is that, phosphate rock (PR) generally requires P-deficient acidic soils with pH of less than 6.2 for P to be released and become available for uptake. Application of PR in neutral to slightly alkaline to soils (pH

>6.2) is therefore discouraged since PR solubility is very low in such soils and therefore can not supply sufficient available P to plants. Phosphate solubilizing bacteria have a capability among others, of producing organic acids which in turn lowers the local acidity of the soil in which they operate. The lowering of the pH will/may bring about right conditions for solubility of MPR.

Maize trials were established in two villages (Nghumbu and Mlali) of Kongwa District to assess effectiveness of PSB in solubilizing MPR in neutral to slightly alkaline soils and two factors were tested, which are field characteristics (in which treatments were sites), the second factor was PSB co-applied with MPR. Maize trials were established using randomized complete block design (RCBD), the seven sites ,PSB inoculum co-applied with different rates of Minjingu phosphate rock (MPR) (0 – 60 kg ha^{-1}). Limiting nutrients such as N and S were corrected then Minjingu RP was applied as basal fertilizer during planting by placing it below the seed and covering with a thin layer of soil followed by a co-culture of PSB inoculant at 5 mL (10^9 bacteria per litre) poured around each plant four days after emergence. Maize plants were harvested at maturity then grain and straw samples were analysed for N, P and K content, phosphorus uptake and phosphorus use efficiency were calculated.

Using the soil data, it was found that Nitrogen was the main limiting nutrient in all seven fields. The limiting nutrients in Nghumbi were N and K while N, P, K and Zn were limiting nutrients in Mlali village. In the trial fields, the main effect of fields' characteristics indicated that the performance of maize and its analyzed parameters (N, P, K, S, Mg, Ca, Na, Zn, Cu, Fe and Mn) were significant ($P < 0.001$) across the fields reflecting heterogeneity in nutrient levels. There was no significant effect of PSB treatments on maize grain yield and straw yield. Results also did not show significant (P

=0.427) interaction effects of field characteristics and treatment combinations on the measured variables in maize because of draught experienced in the study area.

The findings of the present study, apart from setting site-specific fertilizer recommendations, also suggest that the performance of maize in the study area depends on the soil nutrient status, especially for native P, N, and K. The studied soils need external nutrient inputs and proper management to optimize crop production and more research is recommended on PSB for more than one season in neutral to slightly alkaline soil before ascertaining the technology to farmers because in this season PSB did not enhance solubility of MPR due to draught experienced in the study area.

DECLARATION

I, Daniel Masumbuko Nhunda, do hereby declare to the Senate of Sokoine University of Agriculture, that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

………………………………… ………………………

Daniel Masumbuko Nhunda **Date**

(MSc. Candidate)

The above declaration is confirmed by;

………………………………… ………………………

Prof. Johnson Semoka **Date**

(Supervisor)

………………………………… ………………………

Dr. Hamisi Tindwa **Date**

(Supervisor)

COPYRIGHT

ACKNOWLEDGEMENTS

First of all, I would humbly like to thank the Almighty God who has been with me in all my life to this stage. I bow and glorify God for his merciful love, protection and guidance to me and my family during MSc studies.

I highly thank and appreciate my academic supervisors namely Prof. Johnson Semoka and Dr. Hamisi Tindwa for their tireless academic guidance, support and encouragement during my MSc studies from coursework, research proposal development and finally during this research work.

I would like to convey my sincere gratitude and thanks to farmers in Kongwa District who allowed me to work and take soil samples from their fields. Mr. Loti who was the lead farmer in two villages, deserves a word of thanks on behalf of all farmers in the area for his continuous and tireless participation and support during my field work in Kongwa District.

My sincere thanks are also directed to the Soil Science Laboratory technicians and technologists from the Department of Soil and Geological Sciences of Sokoine University of Agriculture for their support. These are Ms. P. Mtanke, Mr. Amour M. Suleiman, Mr. Alphonce C. Mgina, Mr. Louis L. Mdoe and Mr. Pelegy Stevenson.

I am also grateful to all academic staff in the Department of Soil and Geological science for their day to day academic and social support in my research work.

Furthermore, I am very thankful for the administrative and academic support provided to me during my MSc studies by Dr. Nyambilila A. Amuri and then Dr. Hamisi Tindwa (Heads of Department of Soil and Geological Sciences) and other administrative staff at the Department.

I lastly take this opportunity to thank my fellow MSc students for their cooperation during coursework and Research part of this MSc studies, namely; Raphael Damiano, Grace Mpinda and Maduhu Yumbu.

DEDICATION

To Almighty God, my beloved parents Mr. and Mrs Mwebeya Nhunda who laid the foundation of my career. My special dedication is addressed to my lovely wife, Ester Daniel and my children; Sarah, Neema, Laurian, Baraka and Daniela, who missed me a lot when I was undertaking the course of my study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATION AND SYMBOLS

Al	Aluminum
BS	Base Saturation
C: N	Carbon to Nitrogen ratio
Ca	Calcium
Ca2+	Calcium ion
CEC	Cation Exchange Capacity
CEC	Cation Exchange Capacity
EC	Electrical conductivity
EC1:2.5	Electrical conductivity of the soil to water suspension
ESP	Exchangeable Sodium Percentage
et al.	et alia
FAO	Food and Agriculture Organization of United Nations
Fe	Iron
g	gram
GIS	Geographic Information System
GPS	Global Positioning System
ha	hectare
HCO3-	Bicarbonate ion
K+	Potassium ion
Kg	kilogram
m.a.s.l.	Meters above sea level
Mg^{2+}	Magnesium ion
mm	millimeter
MPR	Minjingu Phosphate Rock

MSc	Master of Science
N	Nitrogen
Na^+	Sodium ion
NO_3^-	Nitrate ion
O	Oxygen
^oC	degree Celsius
OC	Organic carbon
OM	Organic Matter
P	Phosphorous
pH	Potential of hydrogen
PSA	Particle Size Analysis
PSB	Phosphorus Solubilizing bacteria
PSM	Phosphorus Solubilizing microorganism
r	Correlation coefficient
R^2	Coefficient of determination
S	Sulphur
SAR	Sodium Adsorption Ratio
SO_4^{2-}	Sulphate ion
SUA	Sokoine University of Agriculture
t	ton
TN	Total Nitrogen
USDA	United States Department of Agriculture

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background Information

Maize (*Zea mays L.*) is the most cultivated cereal in the world. Its economic importance is being manifested by the different ways of consumption: that is from human food and animal feed to the high technology industry (Edwards, 2009). Maize contributes 60% of dietary calories to Tanzanian consumers (Rose, 2011). The cereal also contributes more than 50% of utilizable protein (Jilo, 2022). The crop is cultivated on an average of two million hectares, or about 45% of the cultivated area in Tanzania. Realizing the importance of the maize crop in Tanzania, the government has been committing human and financial resources to develop agricultural sector (Rose, 2011). With all the great contributions of maize in the country, yet its cultivation process encounters some constraints such as poor soil fertility especially in semi-arid area leading to low yield and hence, low productivity.

Despite the large area under maize cultivation, average yield in semi-arid Tanzania is about 1.2 t ha^{-1} (Kimaro *et al*., 2009). This is by far below the world's maize average yield which is about 5.2 t ha^{-1} (Karkia *et al*., 2020) and the national average yield of 4.5 t ha^{-1} (Liingilie, 2019). In Kongwa district, the average maize yield is about 1.3 t ha^{-1} but when good agronomic practices used, maize yields range between 3.5 and 4 t ha^{-1} (Kimaro *et al*., 2009). It has been reported that soil fertility decline is one among others factors constraining crop production (Gicheru, 2012). According to Mkoma (2015), nutrient deficiency is a major problem constraining maize production in Kongwa district and the whole of semi-arid regions.

Evidence of plant nutrient deficiencies has been reported in semi-arid areas of central Tanzania (Kimaro *et al*., 2009). According to Kimaro *at el*. (2009), nutrient deficiency is attributed by nutrient removal by crops without adequate fertilization and fixation of the applied phosphorus fertilizers. It is also important to note that even in low-productivity situations, the quantity of nutrients available for recycling via plant and animal residues is rarely sufficient to compensate for the amounts removed in agricultural products (Mushi, 2012).

There is, therefore, a need for improving maize production in Kongwa district that will contribute significantly in enhancing food security, incomes of the farmers and the economy of the district (Katambara *et al*., 2013; Kahimba *et al*., 2013). To optimize maize yield, it requires addressing a number of challenges related to edaphic factors including ensuring availability of plant nutrients such as phosphorus. Reduce nutrient loses through run-off and surface crusting in Kongwa district and other semi-arid. Also, many semi-arid soils have low moisture-holding capacity (Binyam *et al*., 2015). This can be due to inherent low moisture holding capacity of sandy soils which are mostly found in Kongwa (Mkonda and He, 2022).

In Kongwa district, low fertility of soils, especially low in N and available P was reported to be more limiting factor than low and irregular rainfall (Mkoma, 2015). Loss of soil organic matter and nutrients is also a common soil fertility problem in Kongwa (Mkonda, 2018). For example, in semi-arid areas of Central Tanzania, low organic carbon (OC), low total N, low to medium extractable phosphorus (P), medium to high exchangeable potassium (K), low sulphur (S), boron (B) and zinc (Zn) have been reported (Mkoma, 2015). Low levels of plant nutrients are strongly related to little or no replenishment of the soil nutrients.

Phosphorus is an essential nutrient for plants but rendered unavailable for plant uptake due to adsorption onto the surface of soil minerals and precipitation by free Al^{3+} and Fe^{3+} ions (Smit *et al*., 2009). Even where phosphorus is present in the soils in high amounts, its availability to plants is often still problematic due to phosphate -binding in soils (Syers *et al*., 2008). As a result, the efficiency of phosphorus fertilization becomes quite low and hence, requires application of high rates of soluble P fertilizer. Soil pH affects transformation of phosphorus for plants. Applying Minjingu rock phosphate in soils with pH greater than 6.2 will not release its P because the fertilizer is insoluble. A viable alternative to increase MPR solubility in neutral soils and increase plant available P is to combine phosphate rocks (RP) with phosphorus-solubilizing bacteria (Simfukwe, 2016).

Soil microorganisms can increase soil P availability (Jones and Oburger, 2011). Various mechanisms have been proposed to explain the microbial solubilization of P compounds. The mechanisms include: (1) release of organic acids produced during organic residue decomposition (Hameeda *et al*., 2006), (2) excretion of protons due to NH^{4+} assimilation by microorganisms (Illmer and Schinner, 1995); (3) formation of complexes between organic acids/ anions with cations (Al^{3+}, Fe^{3+}, Ca^{2+}) (Welch *et al*., 2002), and (4) solubilization of phosphorus-sorbed onto soil clay and/or oxides (Osorio, 2008). Organic acids produced by microbes also have been reported to help in solubilizing P-compounds (Osorio and Habte, 2009). Equally, P compounds may be solubilized by carbonic acid formed as a result of organic matter decomposition (Osorio and Habte, 2009). An increase in soil P may be caused by several reactions involving microorganisms that produce organic acids and humic substances (Pettit, 2004). Presumably, these substances can replace or compete with inorganic P (Pi- ions) for sorption sites. Mei *et al*. (2021), found that the production of acids was a major mechanism in the solubilization of hydroxyapatite by *Enterobacter agglomerans* under in-vitro conditions. Enhancement of the soil phosphorus availability by phosphate-solubilizing bacteria (PSB) is therefore an effect of products released by microorganisms in soils.

1.2 Problem Statement and Justification

Minjingu phosphate rock is among inorganic P-fertilizers which is widely used to restore soil fertility in agricultural lands of East Africa. The challenge is, phosphate rock (PR) generally requires P-deficient acidic soils with pH of less than 6.2 to be effective (Sanchez and Jama, 2001). Application of PR in slightly acid to neutral soils (pH > 6.2) such as those of Kongwa district is discouraged because PR is insoluble rendering phosphorus from PR unavailable to the plant (Osorio and Habte, 2009). However combining phosphate solubilizing bacteria (PSB) with MPR makes the insoluble PR in slight acid and neutral soils available to plants by producing organic acids that lowers the soil pH (Yousefi *et al*., 2011). The PSB also create acidity by evolution of CO_2 as observed in solubilization of calcium phosphates (Yousefi *et al.*, 2011). Production of organic acid coupled with the decrease of the pH by the action of microorganisms result in P solubilization contained in PR. Increasing P availability in soils of Kongwa district through co- application of MPR and phosphorus solubilizing bacteria may lead to increased crop production.

1.3 Objectives

1.3. 1 Overall objective

The overall objective of this study was to increase phosphorus availability in soils for sole- maize cropping systems in Kongwa district through microbial solubilization of Minjingu phosphate rock.

1.3.2 Specific objectives

Specific objectives of this study were;

i. To determine the status of plant available nutrient elements and physical chemical properties from soils of selected villages in Kongwa District.
ii. To evaluate effects of field characteristics on maize response
iii. To determine the response of maize to different levels of Minjingu phosphate rock fertilizer.
iv. To determine effectiveness of P- solubilizing bacteria (PSB) in enhancing P availability from Minjingu phosphate rock to maize in selected slightly acid to neutral soils.

1.4 Organization of the Dissertation

This part describes format of the thesis. Chapter one presents general introduction, providing the study's theoretical background information as well as introducing the problem statement and justification of the study. This chapter also, has general and specific objectives of the study.

Chapter two covers aspects related to soil fertility status in Tanzania and review of food production. It also includes physical and chemical properties of soils of Kongwa District. Chapter three is on enhancing availability of P from MPR by using phosphorus solubilizing bacteria in slightly alkaline to neutral soils of Kongwa in Dodoma region.

References

Binyam, A. Y. and Desale, K. A. (2015). Rainwater harvesting: An option for dry land agriculture in arid and semi-arid Ethiopia. *International Journal of Water Resources and Environmental Engineering* 7(2): 17-28.

Edwards, J. (2009). Maize growth and development. *Maize growth and development.* 60pp.

Gicheru, P. (2012). An overview of soil fertility management, maintenance, and productivity in Kenya. *Archives of Agronomy and Soil Science* 58(sup1), S22-S32.

Hameeda, B., Reddy, Y., Rupela, O. P., Kumar, G. N. and Reddy, G. (2006). Effect of carbon substrates on rock phosphate solubilization by bacteria from composts and macrofauna. *Current Microbiology* 53(4): 298-302.

Illmer, P., Barbato, A. and Schinner, F. (1995). Solubilization of hardly-soluble $AlPO_4$ with P-solubilizing microorganisms. *Soil Biology and Biochemistry* 27(3): 265-270.

Jilo, T. (2022). Nutritional benefit and development of quality protein maize (QPM) in Ethiopia. *Cereal Research Communications*, *50*(4), 559-572.

Jones, D. L. and Oburger, E. (2011). Solubilization of phosphorus by soil microorganisms. In: *Phosphorus in action*. Springer, Berlin, Heidelberg. pp. 169-198.

Kahimba, F. C., Kombe, E. E. and Mahoo, H. F. (2013). The potential of system of rice intensification (SRI) to increase rice water productivity: A case of Mkindo irrigation scheme in Morogoro region, Tanzania. *Tanzania Journal of Agricultural Sciences* 12(2).

Karkia, M., Pantha, B. P., Subedia, P., GCa, A., & Regmib, R. (2020). Effect Of Different Doses Of Nitrogen On Production Of Spring Maize (Zea Mays) In Gulmi, Nepal. *Sustainability in Food and Agriculture (SFNA)*, *1*(1), 1-5.

Katambara, Z., Kahimba, F. C., Mahoo, H. F., Mbungu, W. B., Mhenga, F., Reuben, P. and Nyarubamba, A. (2013). Adopting the system of rice intensification (SRI) in Tanzania: A review. *Agricultural Sciences* 8(4):1-7.

Kimaro, A. A., Timmer, V. R., Chamshama, S. A. O., Ngaga, Y. N. and Kimaro, D. A. (2009). Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops. *Agriculture, Ecosystems & Environment* 134(1-2): 115-125.

Mei, C., Chretien, R. L., Amaradasa, B. S., He, Y., Turner, A. and Lowman, S. (2021). Characterization of phosphate solubilizing bacterial endophytes and plant growth promotion in vitro and in greenhouse. *Microorganisms* 9(9).

Mkoma, A. (2015). *Response of maize to phosphorus in sole maize and maize-pigeonpea cropping system in semi-arid areas of Tanzania* (Doctoral dissertation, University Of Dodoma).

Mkonda, M. Y. (2018). *Soil Organic Carbon Accumulation, Climate Variability and Crop Production in Tanzania's Semi-arid Agro-Ecological Zone: A Case Study of the*

Kongwa District. Doctoral Dissertation for Award of the Degree of Doctor of Philosophy in Agricultural Resources and Environment of the Southwest University 166.

Mkonda, M. Y. and He, X. (2022). The influence of soil organic carbon and climate variability on crop yields in Kongwa District, Tanzania. *Environmental Management* 2022: 1-9.

Mushi, D. P. (2012). *Factors constraining food security in Dodoma region: a case study of Chamwino district*, *Tanzania.* Doctoral Dissertation for Award Degree at the University of Dodoma.141pp.

Osorio, N. W. (2008). Effectiveness of microbial solubilization of phosphate in enhancing plant phosphate uptake in tropical soils and assessment of the mechanisms of solubilization. [http://hdl.handle.net/10125/20389] site visited on 15/09/2021.

Osorio, N. W. and Habte, M. (2009). Strategies for utilizing arbuscular mycorrhizal fungi and phosphate-solubilizing microorganisms for enhanced phosphate uptake and growth of plants in the soils of the tropics. In *Microbial strategies for crop improvement*. Springer, Berlin, Heidelberg. pp. 325-351.

Pettit, R. E. (2004). Organic matter, humus, humate, humic acid, fulvic acid and humin: their importance in soil fertility and plant health. *CTI Research* 10: 1-7.

Rose, M. (2011). The dietary importance of maize in Katumba ward, Rungwe district, Tanzania, and its contribution to household food security. *African Journal of Agricultural Research* 6(11): 2617-2626.

Sanchez, P. A. and Jama, B. A. (2001). Soil fertility replenishment takes off in East and Southern Africa. In: *Integrated plant nutrient management in sub-Saharan Africa: from concept to practice*. Wallingford UK: CABI Publishing. pp. 23-45.

Simfukwe, E. J. (2016). *Isolation and characterization of phosphate rock-solubilizing microorganisms from soils and rock phosphate samples of Panda Hill and Minjingu, Tanzania*.Doctoral dissertation, Sokoine University of Agriculture.https://ir-library.ku.ac.ke › bitstream › handle › E...PDF] site visited on 12/08/2021.

Smit, A. L., Bindraban, P. S., Schröder, J. J., Conijn, J. G. and Van der Meer, H. G. (2009). *Phosphorus in agriculture: global resoources, trends and developments: report to the Steering Committee Technology Assessment of the Ministery of Agriculture, Nature and Food Quality, The Netherlands, and in collaboration with the Nutrient Flow Task Group (NFTG), supported by DPRN (Development Policy review Network)* (No. 282). Plant Research International 42.

Syers, J. K., Johnston, A. E. and Curtin, D. (2008). Efficiency of soil and fertilizer phosphorus use. *FAO Fertilizer and Plant Nutrition Bulletin* 18(108).

Welch, S. A., Taunton, A. E. and Banfield, J. F. (2002). Effect of microorganisms and microbial metabolites on apatite dissolution. *Geomicrobiology Journal* 19(3): 343-367.

Yousefi, A. A., Khavazi, K., Moezi, A. A., Rejali, F. and Nadian, H. A. (2011). Phosphate solubilizing bacteria and arbuscular mycorrhizal fungi impacts on inorganic phosphorus fractions and wheat growth. *World Applied Science Journal* 15(9): 1310-1318.

CHAPTER TWO

2.0 ASSESSMENT OF SOIL FERTILITY STATUS IN SELECTED FIELDS UNDER MAIZE PRODUCTION IN KONGWA DISTRICT, DODOMA REGION, TANZANIA

Abstract

This study was conducted in Kongwa District to assess fertility status of soils of selected fields under maize production. The aim of this study was to understand fertility variability among soils and recommend appropriate fertilizer rates. The study involved 24 randomly selected maize fields. Composite soil samples were collected in these fields at 0–20 cm deep and characterized for soil fertility status. Soil physical chemical parameters were analysed using Laboratory standard methods. Results indicated that 48% of the soils were sandy clay loam and 26% were sandy loam and 26% had clay or loamy sand textural classes. The soil pH ranged from 3.52 to 7.7, organic carbon ranged from very low to medium (0.19-1.60%) and total N were very low to low (0.01-015%). Results indicated further that 42% of the soils had P deficiency and 16.7% had inadequate S. In addition, 45.8% of the soils had inadequate exchangeable K and exchangeable Mg were very low to high (0.29-4.06cmol$_{(+)}$ kg^{-1}). Exchangeable Ca was low to very high (1.06 to 10.04 cmol$_{(+)}$ kg^{-1}) with favourable base saturation for crop production. The CEC ranged from very low (2.62cmol$_{(+)}$ kg^{-1}) to medium (18.9 cmol$_{(+)}$ kg^{-1}). Extractable micronutrients such as Cu, Fe, and Mn were adequate but Zn was inadequate in 58% of the soils. The study area showed that fertility is low with inadequate N, P, K, Zn, Mg, and Ca while nutrient balance had favourable Ca: Mg and unfavourable Mg: K. Hence, the studied soils need external nutrient inputs and proper management to optimize crop production.

Keywords: Fertilizer recommendations, maize, micronutrients; Soil fertility; Soil properties; Tanzania.

2.1 Introduction

Soil fertility is the ability of the soil to provide all essential plant nutrients in the available forms and in suitable balance. Decline in soil fertility has remained one of the most important factors explaining the significant gap observed between potential and actual food production in sub- Saharan Africa (Sanginga and Woomer, 2009). It has been widely acknowledged that poor soil fertility is the principal constraint to smallholder farmers in Africa. Factors that cause poor soil fertility in semi- arid regions includes cultivating continuously for many years without or with little fertilizer input use, and soil erosion have decreased the soil nutrient reserves to very little plant nutrient levels (Moswetsi *et al*., 2017). Poor soil fertility occurs mainly when the removed plant nutrients from the soil exceeds their replenishment, resulting in negative balance of plant nutrients.

It has been reported that, in all cropping systems in Tanzania, more nutrients are leaving the system than are being added (Moswetsi *et al*., 2017). Of all the plant nutrients, nitrogen (N) is commonly deficient in soils (URT, 2000). In Tanzania, annual N depletion rates range from 20 to 40 kg ha^{-1} (Gidago *et al.*, 2011). Research on soil fertility assessment conducted in the Southern highland Tanzania showed that 77% of the studied soils had very low to low N content (Koskikala *et al*., 2020). N is continuously lost from the soils through microbial denitrification, leaching, chemical volatilization, soil erosion and removal of N- containing crops (Chenand Graedel, 2016). The N reserves in most agricultural soils including those in Kongwa district must therefore be replenished in order to maintain adequate level of crop production.

Phosphorus (P) is another plant nutrient required in large quantities but usually available in limited amount in semi-arid soils. P occurs in limited amounts because of soil erosion, losses and fixation due to high clay content and metal oxides as a result of weathering activities (Mabagala, 2022). Availability of P for agricultural crop uptakes in semi- arid soils from P containing fertilizers depends on the sorption capacity of the soil to hold it from losses, soil pH and metal cations (Mardamootoo *et al*., 2021), and P saturation degree of the soil which determines additional P to be added to the soils and held safely with minimum losses to the environment (Mardamootoo *et al*., 2021). Generally, 70- 90 % added P through fertilization in the soils is fixed depending on soil characteristics, resulting in reduced plant available P (Bekele *et al*., 2020), consequently increased P fertilizer application rates and blanket recommendations are adapted in agricultural fields (Bekele *et al*., 2020).

Studies have as well shown that, the characteristics of well drained soils of semi-arid areas often old weathered and leached Ultisols or Oxisols, intensify the soil fertility problem with regard to N, P, K and other nutrients (Nweke and Ilo, 2019). Soil survey carried out by Msanya *et al*. (2018) in Dodoma district, central semi-arid region Tanzania also reported low nutrient status especially with respect to N, P and Zn. These results concur with those found by Mkoma (2015) who reported very low contents of N (0.04 -0.11%) and low P (4.17 -7.16 mg P kg^{-1}) in Kiteto districts. Soils in semi- arid regions have low organic content and low clay percent, all of which act as storehouse of positively charged plant nutrients such as Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} (Msanya *et al.,* 2018). Because of low clay and organic content which are negatively charged and hence responsible for holding up the positively charged cations, soils easily loss positively charged cations through leaching, soil erosion and through crop removal from the fields.

Medium contents of Ca, Mg, K and Na were reported in Kiteto district (Mkoma, 2015), this information is concurrent with results obtained from soils of Dodoma district (Msanya *et al.,* 2018). Plants also require micronutrient such as B, Fe, Mn, Zn and Cu although in low concentration. The incidence of micronutrients deficiency has markedly increased in recent years due to intensive cropping, loss of top soils by erosion, through leaching, liming of acid soils, decreased proportions farm yard manure compared to chemical fertilizers and use of marginal lands for crop production (Ram *et al.*, 2017). Factors such as pH, redox potential, biological activities, soil organic matter and clay content are important in determining micronutrients in soils (Ram *et al.*, 2017). The study by Msanya *et al*. (2018) reported that soils in Dodoma central Tanzania have adequate micronutrients for crop production i.e., Fe, Mn and Cu except for Zn. These results are similar to those reported by Mkoma (2015) from studies conducted in Kiteto district. Sulphur (S) is another plant nutrient which is increasingly being recognized as the fourth major nutrient after N, P and K in crop production (Verheye, 2006). Inorganic S is much less abundant in agricultural soils (Scherer, 2001) as compared to organic S the form which is not available to plants. Sulphur may precipitate in the form of SO_4^{2-} as calcium, magnesium or sodium sulphate. It also occurs as co-precipitated impurity with $CaCO_3$ and is an important fraction of total S in calcareous soils (Scherer, 2001).

Many research works conducted address the problem of low soil fertility as a result of poor soil management, but little information is available on the status of each plant nutrients such as N, P, K, and micronutrients and ways to manage the soils especially in Kongwa district is available. In addition, no fertilizer recommendations for each of the nutrients in semi- arid zones of central Tanzania have been established (Rurinda *et al*., 2020; Mowo *et al.*, 1993; Marandu *et al*., 2014) except for N. Information emerging from this study is important to decision makers, policy makers and farmers in regard to food security, agriculture and food production.

The overall objectives of this study were therefore to assess soil fertility while specific objectives were to determine the status of each plant nutrient elements, to determine the response of maize to different levels of Minjingu rock phosphate, to determine effect of soil characteristics of each site on maize crop and determine effectiveness of P solubilizing bacteria in enhancing P availability from Minjingu rock phosphate to maize and demystify ways of semi-arid soil fertility management. Results of this study will provide information that will be used scientists and other stakeholders for fertilizer recommendations to regions with similar characteristics with Kongwa. Soil fertility assessment is the tool for measuring available plant nutrients and estimation of capacity of the soil to maintain a continuous supply of nutrients to plant (Stockdale *et al.,* 2002). It is considered a most basic decision-making tool on a particular land use system and provides information on nutrient availability in the soils. Furthermore, the tool helps to establish appropriate fertilizer management strategy to for purpose of improving soil fertility and crop productivity (Stockdale *et al*., 2002).

Farmers in Kongwa try to maintain and improve soil fertility through annual crop rotation such as groundnuts, pigeon pea, sunflower and sesame. However, this practice is not sufficient to compensate mined plant nutrients from the soils and provide adequate plant nutrition (Karlen *et al.,* 2002). The practice of crop rotation which involves the sequential production of different plant species on the same land has been in existence for many years but not sufficient by itself (Karlen *et al.,* 2002). Crop rotation is just one component in soil fertility management and thus integrated soil fertility management (ISFM) is the proper tool to ensure soil quality.

Integrated soil fertility management (ISFM) is a tool currently adapted by the science community dealing with soil fertility management. The ISFM tool can be defined as the development of adaptable and sustainable soil management practices that integrate social, biological, chemical, cultural and economic processes that regulate soil fertility (Vanlauwe *et al*., 2006). ISFM advocates the utilization of locally available resources, the combined application of organic and inorganic fertilizers in their appropriate rates and enhancement of use efficiency of both inputs (Vanlauwe, 2004). Deploying ISFM will certainly help smallholder farmers in the study area to address the acute problem of poor soil fertility and finally maximize production. To achieve the main goal of the study, these were the specific objectives; assess soil fertility of selected fields to identify status of plant nutrients, identify and grouping limiting nutrients into fertility groups and perform field specific fertilizer recommendations.

2.2 Materials and Methods

2.2.1 Description of the study area

This study was conducted in selected fields of maize cropping systems in Kongwa district, Dodoma region, the semi-arid zone of Central Tanzania. The twenty four fields were located between 6^{o}15'30" to6^{o}19'43"S and 36^{o}37'59" to 36^{o}51'00" E (Fig.2.1).The elevation of the study area ranges from 900 to 1000 metre above sea level (m.a.s.l.). The area is on the leeward side of Ukaguru mountains with bush or thicket type of vegetation. The total annual precipitation is about 400 to 600 mm with a peak rainfall experienced in December. The mean annual temperature is 26 °C. According to the World Reference Base for Soil Resources (WRB), the soils of the district are classified as Chromic Luvisols with sandy loam texture (FAO, 1988).

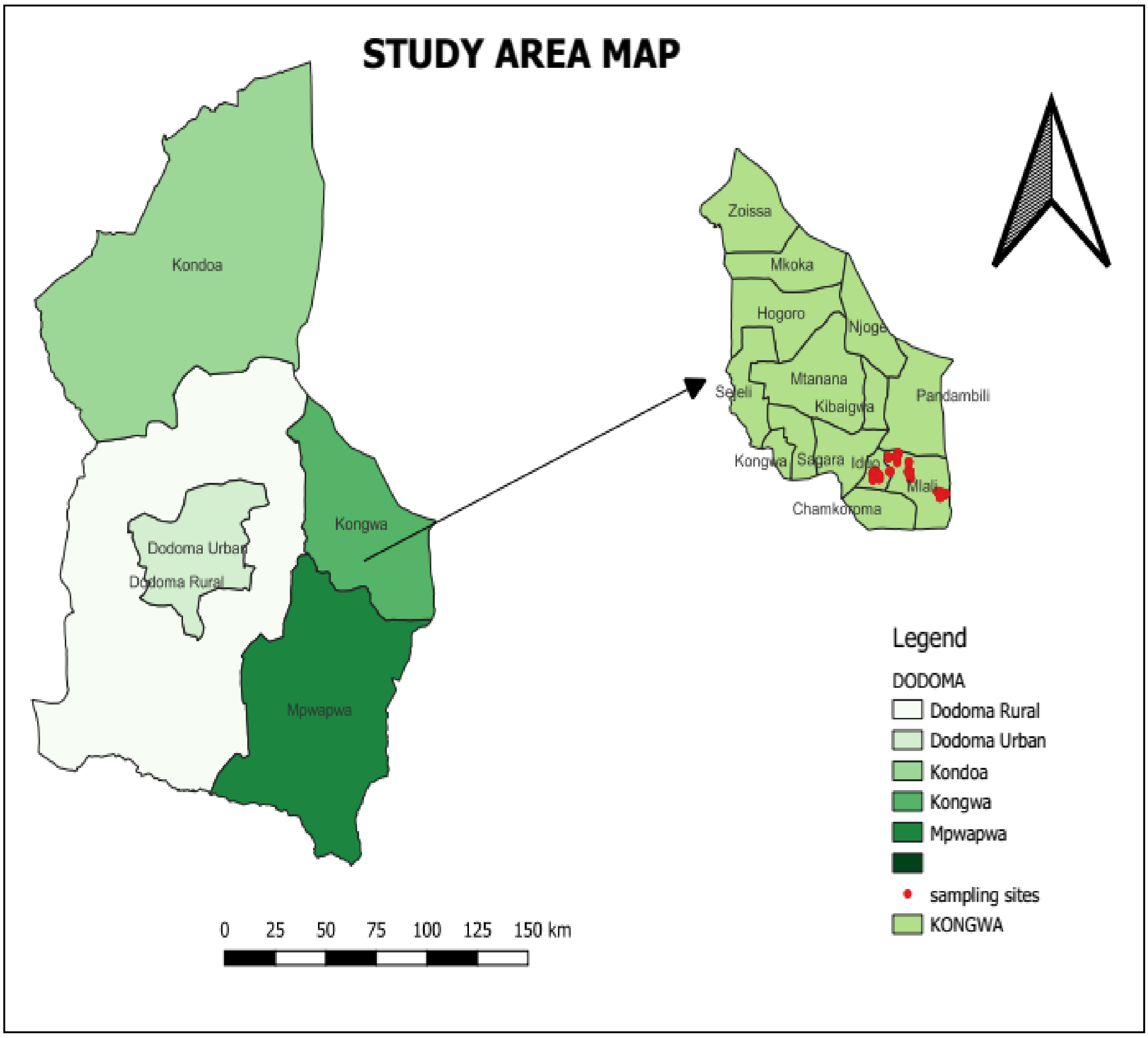

Figure 2.1: Map of Kongwa District showing sampling sites in the selected villages

2.2.2 Site selection and soil sampling

Four villages (Ihanda, Iduo, Mlali and Nghumbi) in Kongwa district, which are involved in maize production were randomly selected among 12 villages in two wards (Mlali and Ihanda) (Appendix 1). The distance from each selected villageto one another ranged between 12.7 to 21.9 km.

Composite soil sample from each field was collected at 0-20 cm deep. The composite soil sample of each field was obtained from at least 11 spots selected in a zig-zag pattern over the whole field of about 800 m^2. Each composite soil sample was about 1 kg. After sampling, all composite soil samples were transferred to the laboratory for analysis.

2.2.3 Soil analysis

Soils were subjected to laboratory analysis in the Soil science Laboratory of the Sokoine University of Agriculture, in Tanzania. Particle size distribution was determined by the Bouyoucos hydrometer method (Okalebo, 2002) after dispersing the soils with sodium hexametaphosphate followed by determining textural class using the USDA textural triangle (Okalebo, 2002).Organic carbon was determined by the Walkley-and Black wet oxidation method by Nelson and Sommers (1982) and total nitrogen (TN) by the micro-Kjeldahl procedure (Loria and Sowyer, 2005). Available P was extracted using Bray-1 for acidic pH and Olsen methods for alkaline pH (Bray and Kurtz, 1945) and measured by Spectrophotometer following colour developed by molybdenum blue method (Murphy and Riley, 1962). Exchangeable bases were extracted by ammonium acetate saturation method (Thomas, 1986). Cation exchange capacity was determined from NH_4^+ saturated soil colloids and displaced using 1 M KCl, then determined by Kjeldahl distillation method for estimation of cation exchange capacity (CEC) of the soil (Robertson and Philip *et al.,* 1999). Extractable sulphur ($SO_4^{2-}S$) was extracted using calcium monophosphate ($Ca(H_2PO_4)_2.H_2O$), then determined by the turbidimetric method as described by Moberg (2001). The EC for soil samples from Kongwa was measured by using EC meter in a 1:2.5 soil: water (or $CaCl_2$ for pH only) extract as described by McLean and Oldham (1982).Extractable metallic micronutrients (e.g., Cu, Fe, Zn and Mn) were extracted by diethylene triamine-pentacetic acid (DTPA) as described by Lindsay and Norvell (1978). Concentrations of Fe, Zn and Mn were determined by atomic absorption spectrophotometer. Total exchangeable bases (TEB) were calculated as the sum of exchangeable bases Ca, Mg, K and Na whereas nutrient ratios such as Ca:Mg and Mg:K were calculated from the quantities of exchangeable bases.

2.2.4 Identification of limiting nutrients and soil fertility groups

Each nutrient parameter was interpreted through rating against published thresholds (e.g., low or sufficient) using the recommended critical values for rating chemical and physical soil parameters (Landon, 1991). Soil fertility groups were established on the basis of limiting nutrients for each field. Fields having the same limiting nutrients were placed in a particular soil fertility group. This was done in order to establish a basis for making field specific fertilizer recommendations.

2.3 Results and Discussion

2.3.1 Particle size distribution

The soil textural classes ranged from clay to sandy loam. The study area is largely dominated by sandy clay loam soils (48%) and less by sandy loam soils (26%).According to Kyveryga *et al*. (2009), sandy clay loam (SCL) and sandy loam (SL) textured soils are suitable for maize production because they are capable of holding water for relatively longer period than other textures; they are good in infiltrating air and water and can hold nutrients. Soil texture affects absorption of nutrients, microbial activities, the infiltration and retention of water, soil aeration, tillage, and irrigation practices (Gupta, 2004. Sandy clay loam soil, being a mix of both (i.e sand and clay), have moderate pore size which is beneficial for plant growth. The soil holds nutrients and favours microbial activities especially when organic matter is in sufficient amount.

Table 2.1: Particle size distribution of the study soils of each field in four villages - Kongwa District

VILLAGE	FARM NO.	Particle size distribution and textural classes			
		Clay (%)	Silt (%)	Sand (%)	Textural Class
IHANDA	1	25.4	0.92	73.68	SCL
	2	58.4	10.92	30.68	CL
	3	13.4	2.92	83.68	LS
	4	30.4	2.64	66.96	SCL
	5	36.4	2.64	60.96	SC
	6	22.4	1.64	75.96	SCL
NGHUMBI	1	24.4	8.64	66.96	SCL
	2	17.4	1.64	80.96	SL
	3	17.4	3.64	78.96	SL
	4	25.04	13.28	61.68	SCL
	5	23.04	1.28	75.68	SCL
MLALI	1	11.04	1.28	87.68	LS
	2	17.04	3.28	79.68	SL
	3	43.04	0.28	56.68	SC
	4	37.04	1.28	61.68	SC
	5	20.04	0.28	79.68	SCL
	6	21.04	0.28	78.68	SCL
IDUO	1	17.04	0.28	82.68	SL
	2	20.04	4.28	75.68	SCL
	3	59.04	6.28	34.68	C
	4	22.04	1.28	76.68	SCL
	5	28.04	2.28	69.68	SCL
	6	55.04	3.28	41.68	C

Key: SCL = sandy clay loam, SL = sandy loam, C= clay, LS = loamy sand, SC =Sandy clay (Farm No. Stand for sites and names of the farm owners, Appendix 1)

2.3.2 Soil pH, EC, total nitrogen, organic carbon, extractable phosphorus and extractable sulphur

Soil pH, total nitrogen, organic carbon, phosphorus, and sulphur of the studied soils were as presented in Table 2.3. The pH of the study soils ranged from 3.52 (extremely acid) to 7.7 (moderately alkaline). Soil reaction (pH) is an indication of the acidity or alkalinity of the soil. Soil pH has high influence on the solubility of micronutrients and availability of macronutrients in soils (Giller, 2001b; Brady and Weil, 2017). The soils at Ihanda village were with extremely acid pH (3.52-5.36), this can limit growth of most crops including maize. In Nghumbi village, pH was nearly neutral and ranged from 6.7 to 7.1; this range favours growth of most crops including maize. Mlali had a pH ranging from 6.5 to 7.6 while Iduo village had pH ranging from 5.6 to 6.7. The trend was such that Nghumbi> Mlali> Iduo>Ihanda, where Nhumbi soils are less acidic as compared to those of Ihanda.

Table 2.2: Soil pH, EC, total N, OC, extractable P, S and limiting nutrients in the twenty-four farmer's fields in Kongwa District –Dodoma

Village	Farm No.	Soil pH_{H2O}	EC	TN	OC	Ext.P		S	Limiting nnutrients
						(Olsen)	(Bray-1)		
			(dS m^{-1})	(%)		(mg kg^{-1})			
IHANDA	1	4.81	0.055	0.01	0.19*l*		7.53*l*	3.43*l*	N, P and S
	2	4.23	0.077	0.1	0.93 *l*		12.00s	11.81s	N
	3	5.36	0.038	0.03	0.24*l*		5.86*l*	14.81s	N and P
	4	4.65	0.067	0.1	0.93 *l*		9.91*l*	20.48s	N and P
	5	3.52	0.091	0.07	0.74 *l*		2.80*l*	19.80s	N and P
	6	4.39	0.051	0.08	0.78*l*		2.24*l*	19.69s	N and P
NGHUMBI	1	7.05	0.207	0.15	1.11*l*	38.61s		10.33s	N
	2	7.06	0.192	0.09	1.11*l*	53.51s		16.72s	N
	3	7.1	0.118	0.07	0.74 *l*	29.86s		17.41s	N
	4	6.69	0.168	0.11	1.26s	19.79s		13.07s	N
	5	6.99	0.1	0.05	0.59*l*	22.09s		21.73s	N
MLALI	1	6.82	0.11	0.12	1.49s	8.59*l*		10.24s	N and P
	2	7.6	0.077	0.06	0.62*l*	8.25*l*		33.01s	N and P
	3	6.48	0.098	0.04	0.65 *l*	8.59*l*		20.65s	N and P
	4	7.22	0.151	0.02	0.30*l*	11.11s		21.31s	N
	5	7.7	0.124	0.12	1.60s	8.64*l*		19.46s	N and P
	6	7.63	0.211	0.04	0.63 *l*	9.19*l*		14.43s	N and P
IDUO	1	6.27	0.182	0.01	0.19			6.50*l*	N and S
	2	6.72	0.07	0.02	0.38*l*		5.09*l*	8.45*l*	N and P
	3	6.28	0.312	0.09	0.93 *l*		4.24*l*	4.26*l*	N, P and S
	4	5.56	0.125	0.07	0.89 *l*		0.90*l*	8.68s	N
	5	5.83	0.065	0.03	0.48*l*		3.28*l*	14.72s	N
	6	6.38	0.138	0.07	0.86 *l*		4.72*l*	9.30s	N

Key: l = low, s= sufficient, ext. P = extractable Phosphorus, TN = total Nitrogen. Categorization is based on Landon (1991)

The EC of soils ranged from 0.038 to 0.312dS m^{-1}). The soils are said to be saline if the EC is greater than 4 dS m^{-1} and pH less than 8.5 (Libutti *et al.*, 2018). The soils with EC less than 4 dS m^{-1} and pH greater than 8.5 are referred to as sodic soils (Visconti *et al.*, 2010). These results show that all soils in the study area are free from salts. This depicts that the soils in the study area are favourable for production of various crops as salts affect normal crop growth.

The total N ranged from 0.01 to 0.15% (Table 2.3) which is rated as very low to low (Bremner, 1965). Budotela (1995) and Letayo (2001) reported very low N content (0.056 % N) in soils of some areas from Dodoma region. N deficiency is a problem of most of the soils in Tanzania, for example Koskikala *et al*. (2020) conducted a study on soil fertility assessment in the Southern highlands of Tanzania and reported that 77% of the studied soils had very low to low N content. N deficiencyin most soils is due to continuous removal of N from the soils through microbial denitrification, leaching, chemical volatilization, soil erosion and removal of N- containing crops (Chen *et al*., 2021). The N reserves in most agricultural soils including those in Kongwa district must therefore be replenished in order to maintain adequate level of maize and other crop production. These provide evidence that N is a limiting nutrient in many soils of the study area. Therefore, the use of nitrogen fertilizers in these soils is necessary to improve crop yields.

Soil organic carbon ranged from very low (0.19%) to medium (1.60%) based on the categorization adopted from Allison (1965), and Brady and Weil (2008). These findings are similar to those from a study done by Budotela (1995) in selected grape producing areas of Dodoma region. Organic carbon plays a vital role in storage of the nutrients such as nitrogen, phosphorus and sulphur. Also, organic matter which is a derivative of OC is important in supplying plant nutrients, enhancing cation exchange capacity, improving soil aggregation and water retention, and supporting soil microbiological activities such as mycorrhizae fungi (Arbuscular mycorrhizae) and plants roots (Rossi, 2009; Usuga *et al*., 2010).Low levels of N and OC in soils of the study area could be attributed to the farming practices adopted by the farmers including slash and burn and removal of crop residues during land preparation leading to a decrease in the biomass and overall organic matter content (Budotela, 1995).

The available phosphorus in the study soils ranged from 0.14 to 53.51 mg kg^{-1} tested by Olsen method and from 0.9 to 12 mg kg^{-1} in soils tested by Bray-1 method. The critical values for P tested by Bray-1 and Olsen methods are 20 and 10 mg kg^{-1} respectively (Landon, 1991). These results showed low status of available phosphorus in 42% of the tested fields. Generally, low content of P was recorded in soils with low pH with an exception of Mlali village which had nearly neutral pH and tested by Olsen method. Low amount in P may be due to fixation by Ca which is highly concentrated in these soils (Table 2.4) Phosphorus is directly affected by pH and not readily available in soils but is available in slightly acid soils with pH ranging from 5.8 to 7.0 (Landon, 1991). When the soil pH is less than 4.5, phosphates (e.g., $H_2PO_4^{2-}$ or HPO_4^{2-}) often combine with iron (Fe) and aluminium (Al) ions to form complex compounds ($Fe(H_2PO_4)_3$ or $Al(H_2PO_4)_3$), which fix P to unavailable forms for plant uptake (Landon, 1991). At high pH values, exceeding 7.5, phosphate ions exist as PO_4^{3-} and easily precipitated by calcium (Ca) to form less soluble compounds and likely to be unavailable to plants (Brady and Weil, 2017).

Extractable S ($SO_4^{-}S$) of the soils ranged from 3.43 to 33.01 (mg kg^{-1}). Sulphur level of 8 mg kg^{-1} is critical, below that response of most tropical crops to S is expected (Landon, 1991). The results of the present study indicated that 16.7% of the soils were inadequate in available S. These results concur with those reported by Imakumbili *et al*. (2019) who conducted a study in Mtwara and found that 63% of the studies soils had low available S. Other studies conducted in Ethiopia reported that S deficiencies are becoming a major problem of soil fertility in tropical soils for crop production (Itanna, 2005). This low level of S is due to nutrient depletion without replenishment. Fertilization recommendations should include the optimum level of S for crop production.

2.3.3 Exchangeable potassium, calcium, magnesium and sodium

Results of exchangeable potassium, calcium, magnesium, and sodium in the studied soils are presented in Table 2.4. Exchangeable potassium in the studied soils ranged from 0.13 to 0.42 $cmol_{(+)}$ kg^{-1} which are rated as very low to medium (Chapman, 1965). According to Landon (1991), application of K fertilizer is recommended when the exchangeable K in loamy soils is less than 0.25 $cmol_{(+)}$ kg^{-1}. The overall results indicated that 45.8% of the studied soils in the study have inadequate exchangeable K. Low exchangeable K in these soils may be caused by primarily the intensity of weathering and the nature of parent material (Msanya *et al.*, 2018) from which they were developed. Msanya *et al.* (2018) reported that the main parent material for soils in Dodoma region is granite which has only 3-5% of potassium oxide. Another reason may be due to continuous cultivation for several seasons without replenishing of K nutrient using fertilizer materials rich in K (Ashraf *et al*., 2002). Therefore, these soils require application of K containing fertilizers.

Table 2.3: Concentrations of exchangeable bases in the studied soils of Kongwadistrict

Village	Field No.	Potassium	Calcium	Magnesium	Sodium	Limiting nutrients
		(cmol(+) kg-1)				
IHANDA	1	0.15*l*	1.64*l*	0.59*l*	0.14*l*	K, Ca and Mg
	2	0.29s	1.86*l*	0.82s	0.17l	Ca
	3	0.14*l*	2.13s	0.86s	0.12*l*	K
	4	0.22s	1.579*l*	0.726s	0.12*l*	Ca
	5	0.15*l*	1.45*l*	0.51*l*	0.12*l*	K, Ca and Mg
	6	0.11*l*	1.06*l*	0.29*l*	0.14l	K, Ca and Mg
NGHUMBI	1	0.25s	9.14s	3.41s	0.17*l*	
	2	0.29s	8.76s	3.40s	0.21*l*	
	3	0.33s	5.21s	2.38s	0.16*l*	
	4	0.32s	10.04s	4.06s	0.23*l*	
	5	0.21s	6.92s	3.05s	0.16*l*	
MLALI	1	0.14*l*	2.36s	0.77s	0.12*l*	K
	2	0.18*l*	3.68s	1.35s	0.16*l*	K
	3	0.24s	2.47s	1.16s	0.28l	
	4	0.42s	7.55s	2.42s	0.14l	
	5	0.16*l*	5.29s	1.23s	0.12*l*	K
	6	0.16*l*	5.43s	1.55s	0.14*l*	K
IDUO	1	0.31s	3.06s	0.40*l*	0.12*l*	Mg
	2	0.14*l*	2.00s	0.41*l*	0.12*l*	K and Mg
	3	0.32s	3.46s	1.45s	0.16*l*	
	4	0.17*l*	1.31*l*	0.45*l*	0.12*l*	K , Ca and Mg
	5	0.13*l*	2.05s	0.58*l*	0.14*l*	K and Mg
	6	0.23s	3.60s	1.31s	0.12*l*	

Key: S= sufficient, l = low

Exchangeable Mg in the studied soils ranged from 0.29 to 4.04 $cmol_{(+)}\ kg^{-1}$ which was rated as very low to very high with respect to 0.20 $cmol_{(+)}\ kg^{-1}$ level considered as critical concentration (Chapman, 1965). Results depicted that 29% of the selected fields in the study area were inadequate in exchangeable Mg. Furthermore, exchangeable Ca in the study soils ranged from 1.06 to 10.04 $cmol_{(+)}\ kg^{-1}$, which has been rated aslow to very high based on the ratings compiled by Landon, (1991). About 25% of the selected fields in the study area were inadequate in exchangeable Ca. Low Ca content in soils could be due to the low pH values since soils with pH 5.5 or lower are likely to be deficient in Ca (Fernández *et al.*, 2009). This can be seen in Ihanda village in which Ca content is low(Table 2.4) as related to pH which was less than 5 in all farms. Exchangeable Na ranged from 0.12 to 0.28 $cmol_{(+)}kg^{-1}$, the range is between very low to low. This means the soils are not affected by salts hence suitable for a variety of crops. These results for cations are concurrent with what was reported by Mkoma, (2015) who found medium levels of Ca, K, Mg and Na in Kongwa soils. Results also do not divert significantly from those reported by Msanya *et al*, (2018) from the study conducted in Dodoma district, Tanzanaia.

2.3.4 Cation exchange capacity, base saturation and nutrient balances

The cation exchange capacity (CEC), base saturation (BS), and nutrient balances of the studied soils are presented in Table 2.5. The CEC ranged from very low (2.62$cmol_{(+)}$ kg^{-1}) to medium (15.67 $cmol_{(+)}$ kg^{-1}). The low CEC in soils of some fields in the study area could be due to low organic matter content (Merumba *et al.,* 2020), and the dominant clay type (Rhoades, 1982). The soils consist of mainly silca (SiO_2) which is a product of weathering of granitic rocks (Msanya et al., 2018). Generally, soils high in clay are characterized by high CEC but the type of clay can substantially affect the CEC (Havlin *et al*., 1999). Most soils (about 74%) in this study had low clay content (Table 2.2) hence low CEC.

Table 2.4: Nutrient balance levels, base saturation and ratings of the studied soils in Kongwa district

Village	Field No.	CEC (cmol$_{(+)}$ kg^{-1})	Ca:Mg	Mg:K	TEB	BS	Ca:TEB	ESP
IHANDA	1	3.54	2.83*f*	3.58*f*	2.52	67.99	0.65*uf*	6.23
	2	4.17	2.56f	3.87f	3.15	73.07	0.59uf	6.38
	3	4.27	2.58*f*	7.29uf	3.25	74.17	0.66*uf*	4.26
	4	3.67	2.23*f*	3.63f	2.65	72.04	0.59*uf*	4.60
	5	3.24	3.11*f*	3.50*f*	2.22	67.41	0.63*uf*	5.82
	6	2.62	3.75*f*	2.46*f*	1.60	60.93	0.67*uf*	8.54
NGHUMBI	1	13.99	2.70*f*	14.22*uf*	12.97	92.43	0.70*uf*	1.27
	2	13.67	2.62*f*	13.93*uf*	12.65	91.31	0.69*uf*	1.81
	3	9.09	2.21*f*	8.23*uf*	8.07	87.75	0.65*uf*	2.07
	4	15.67	2.46*f*	14.81*uf*	14.65	93.34	0.68*uf*	1.58
	5	11.36	2.26*f*	13.83*uf*	10.34	90.14	0.67*uf*	1.60
	6	10.48	2.03*f*	37.41*uf*	9.46	89.46	0.57*uf*	1.76
MLALI	1	4.40	3.12*f*	5.60*uf*	3.38	76.54	0.69*uf*	3.63
	2	6.39	2.73*f*	10.22*uf*	5.37	83.83	0.68*uf*	2.83
	3	4.76	2.07*f*	4.83*f*	3.78	76.60	0.65*uf*	5.90
	4	10.16	3.15*f*	9.34*uf*	10.53	91.14	0.72*uf*	1.32
	5	9.30	4.09*f*	8.50*uf*	6.80	85.20	0.75*uf*	2.10
	6	8.10	3.31*f*	9.07*uf*	7.29	85.95	0.73*uf*	2.14
IDUO	1	4.22	10.14*uf*	2.98*f*	3.88	75.55	0.76*uf*	4.02
	2	4.53	5.80*uf*	3.21*f*	2.68	71.80	0.74*uf*	4.68
	3	5.00	2.36*f*	7.04*uf*	5.37	83.65	0.64*uf*	2.88
	4	3.51	3.04*f*	3.11*f*	2.05	66.27	0.64*uf*	6.09
	5	3.71	3.54*f*	4.75*f*	2.90	73.43	0.70*uf*	4.85
	6	5.95	2.75*f*	6.94*uf*	5.26	83.68	0.68*uf*	2.31

Key: CEC = cation exchange capacity, Chemical property: Ca=calcium, Mg=magnesium, K=potassium, TEB=total exchangeable bases, f=favourable, uf=unfavourable. Based on Landon (1991).

The base saturation of the studied soils was high and ranged from 66.27% to 93.34%. According to FAO (2006), BS higher than 50% is favourable for crop production. Therefore, most of the soils in the study area are preferably suitable for crop production.

All the fields had favourable soils with Ca: Mg ratio ranging from 2.03 to 4.09 except two farms which had 5.80 and 10.14 while 62% of the fields had unfavourable soils with Mg:

K of >4. The ratios of Ca: Mg ranging from 2 to 4 and those of Mg: K ranging from 1 to 4 are considered favourable for most tropical crops (Msanya *et al*., 2003).

Nutrient imbalances influence nutrient uptake by inducing deficiencies of nutrients, which may be present adequately in the soil (Edem and Ndaeyo, 2009). It is, therefore, important to consider the individual nutrient ratios (i.e., Ca: Mg and Mg: K), which are the indicators of nutrient uptake (Hodges, 2014). The ratios obtained from these soils are the measures used to assess balance between the two essential nutrients. Ca: Mg obtained from this study were generally favourable, this indicate that both Ca and Mg were present in sufficient amount in the study area. Mg: K were generally unfavourable due to insufficient K in most of the soils and therefore K was limiting for maize production. ESP was generally low indicating that soils are not sodic, in other words Na concentration is low and not limiting crop production (Hodges, 2014).

2.3.5 Micronutrients in the study soils of Kongwa

The concentrations of metallic micronutrients (Zn, Cu, Fe, and Mn) in the studied soils are presented in Table 2.6. Extractable Zn ranged from 0.41 mg kg^{-1} to 4.86 mg kg^{-1}.

Table 2.5: Concentrations of four micronutrients in the studied soils of Kongwa District, Dodoma Region, Tanzania

Village	Field No.	Cu	Zn	Fe	Mn	Limiting nutrients
		(mg kg^{-1})				
IHANDA	1	0.74s	0.41*l*	30.62s	42.36s	Zn
	2	1.00s	1.84s	137.01s	46.48s	
	3	0.54s	0.94*l*	31.23s	43.82s	Zn
	4	1.57s	0.73*l*	43.97s	32.10s	Zn
	5	1.17s	0.96*l*	84.42s	34.02s	Zn
	6	0.84s	0.81*l*	71.91s	16.55s	Zn
NGHUMBI	1	1.82s	1.98s	15.61s	50.69s	
	2	2.39s	3.74s	43.73s	34.82s	
	3	2.57s	1.91s	20.48s	60.06s	
	4	4.57s	1.78s	61.27s	105.69s	
	5	2.86s	3.86s	39.11s	73.87s	
	6	2.40s	0.57*l*	37.49s	54.71s	Zn
MLALI	1	1.03s	0.99*l*	25.10s	34.91s	Zn
	2	1.29s	1.23s	18.13s	43.48s	
	3	2.15s	0.94*l*	36.86s	77.75s	Zn
	4	1.43s	0.53*l*	17.53s	55.01s	Zn
	5	1.20s	0.82*l*	15.78s	39.59s	Zn
	6	1.37s	0.56*l*	19.66s	43.87s	Zn
IDUO	1	1.18s	4.23s	20.33s	53.71s	
	2	1.07s	3.15s	27.06s	57.97s	
	3	4.86s	0.89*l*	55.28s	147.18s	Z
	4	2.29s	0.40*l*	48.88s	66.82s	Zn
	5	2.14s	4.42s	46.04s	61.33s	
	6	3.98s	0.57*l*	44.67s	118.16s	Zn

Key: Cu = copper, Zn= zinc, Fe = iron, Mn= manganese,
l = low, s= sufficient. (Landon, 1991)

Iron (Fe), Zinc (Zn), copper (Cu) and Manganese (Mn) are some of the essential metallic micronutrients that participate in various reactions in plant cells or contribute to protein structure. According to Dai *et al*. (2019), responses of crops to Zn application are obtained when soil Zn is 0.6 to 1.0 mg kg^{-1}. However, a critical Zn limit of 1.0 mg kg^{-1} is considered desirable for a range of crops (Landon, 1991). The soils from fourteen among 24 fields selected for this study were inadequate in extractable Zn after being compared with the critical level stated above. Low Zn contents in most of these soils is probably due to high content of free Fe, Al, and Mn ions, which cause adsorption of Zn to non-exchangeable form on their hydrated oxides surface (Buekers and Jurgen, 2007).

Kovacevic *et al*. (2004) reported that, iron (Fe) concentration of 4 mg kg^{1-} of soil interacts antagonistically resulting into decreased availability of Zn. Furthermore, Zn solubility decreases 100 folds for each unit increase in soil pH. This is due to the greater adsorptive capacity of the soil solid surfaces resulted from increased pH-dependent negative charges, formation of hydrolysed Zn and chemisorptions on calcite (Alloway, 2009).

Soil pH controls the availability, solubility and mobility of trace elements including Zn, this determines their translocation in plant (Neina, 2009). At low pH (3.5 to4.8), Zn and other trace elements are usually soluble due to less desorption. At intermediate pH (5.0 to 6.20 the trend of Zn element adsorption increases to almost complete adsorption within a narrow pH range known as pH adsorption edge (Neina, 2009). Brad found that at pH 5.3 the adsorption of Zn was 53% while 50% was sorbed onto humic acid in pH between 4.8 to 4.9 (Neina, 2009).

Extractable Fe ranged from 15.61 to 137.01 mg kg^{-11}. Sims and Johnson (1999) reported that the critical level of Fe for some crops ranged from 2.5 to 5.0 mg kg^{-1}. Based on this critical range, all soils in the present study are adequate in Fe for crop production. Extractable Cu ranged from 0.54 to 4.86 mg kg^{-1}. According to Avci *et al.* (2013), acceptable critical level of Cu ranges from 0.3 to 0.6 mg kg^{-1}. Therefore, the soils of the present study are adequate in Cu for crop production. Extractable Mn ranged from 16.55 to 147.18 mg kg^{-1}. The acceptable critical range of Mn for most crops range from 2.0 to 5 mg kg^{-1} (Avci *et al.*, 2013), suggesting that the studied soils are not limited by extractable Mn for crop production.

2.3.6 Limiting nutrients and soil fertility groups

Results for limiting nutrients and their frequencies of occurrence are presented in Table 2.7. Results indicated that P, K, Mg, Ca, N and Zn were generally the limiting nutrients of which N was limiting in all selected fields, P was limiting in 8 fields, K in 12 fields, Mg in 5 fields, Ca in 6 fields while Sulphur was only limiting in three (3) fields in the study soils (Table 2.7).

Table 2.6: Frequencies of occurrence of each limiting nutrients in 24 fields in selected villages in Kongwa district.

Limiting nutrient	No. of fields it occurs	Percentage (%)
Nitrogen (N)	24	100
Phosphorus (P)	8	33
Potassium (K)	12	45.8
Magnesium (Mg)	5	21.0
Calcium (Ca)	6	25.0
Sulphur (S)	4	16.7
Zinc (Zn)	14	58.3

Data in Table 2.8 show that 12 soil fertility groups were identified and none of them is very extensive over the study area. For example, group 1 which is deficient in N alone occurs in 4 out of 24 fields which is equivalent to 16.7% of the studied fields. The remaining eleven soil fertility groups have two or more limiting nutrients. In general, the results show that there are wide variations in soil fertility of the study soils which call for site specific fertilizer recommendation for optimizing maize production.

Table 2.7: Soil fertility groups and frequencies of their occurrence based on the limiting nutrients in 24 farmers' fields in Kongwa District

Soil fertility group	Limiting nutrient(s)	Frequency of occurrence (No. in %)
Group 1	N	4 (16.7%)
Group 2	N and K	3(12.5%)
Group 3	N, P, K, and Zn	5(20.81%)
Group4	N, P, Ca, Mg, K, and Zn	3(12.5%)
Group 5	N and Zn	2(8.3%)
Group 6	N, Ca, and Zn	1(4.2%)
Group 7	N, K, Mg, Ca, S, and Zn	1(4.2%)
Group 8	N and Ca	1(4.2%)
Group 9	N, P, Mg, Ca, Zn, and S	1(4.2%)
Group 10	N, K, S, and Zn	1(4.2%)
Group 11	N, P, and Mg	1(4.2%)
Group12	N, P, and Zn	1(4.2%)
Total		**24(100)**

Blanket fertilizer recommendations approach is not effective in managing soil fertility problems in the study area. Each soil fertility group needs its own fertilizer recommendation to optimize crop productivity. While only N is needed in soil fertility group 1, soil fertility group 2 needs N and K while soil fertility group 3 needs N, P, K and Zn. Fertilizer types required for group 4 and 7 are those containing N, P, Ca, Mg, K and Zn. Grouping nutrients will lead to site/field specific fertilizer recommendations and deployment of specific soil fertility management strategies based on limiting nutrients (Kihara *et al*., 2016). For nitrogen and P, the rates of 60kg ha^{-1} and 40 kg ha^{-1}respectively may be recommended on the basis of a study by Mkoma (2015) in Kongwa.

2.4 Conclusions and Recommendations

2.4.1 Conclusions

The results of the study show deficiencies in N, P, K, S, Ca, Mg and Zn in study soils. Large variations in nutrient deficiencies exist in the different fields. This led into grouping of soils into twelve soil fertility groups. However, application of nutrients should be made on the basis of each soil fertility group identified.

2.4.2 Recommendations

It is recommended that maize productivity in the study area can be optimized by application of N, P, Ca, S, K and Zn containing fertilizers but this application should be done on the basis of the identified soil fertility groups.

References

Alloway, B. J. (2009). Soil factors associated with zinc deficiency in crops and humans. *Environmental geochemistry and health*, *31*(5), 537-548.

Allison, L. (1965). Organic carbon. *Methods of soil analysis: Part 2 Chemical and Microbiological Properties* 9: 1367-1378.

Ashraf, M., Ashfaq, M. and Ashraf, M. Y. (2002). Effects of increased supply of potassium on growth and nutrient content in pearl millet under water stress. *Biologia Plantarum* 45(1): 141-144.

Avci, H. and Tuğrul, D. (2013). Assessment of trace element concentrations in soil and plants from cropland irrigated with wastewater." *Ecotoxicology and Environmental Safety* 98: 283-291.

Bekele, M., Kebede, F. and Haile, W. (2020). Phosphorus Adsorption-Desorption Isotherm of Lime Treated and Untreated Acid Soils of Assosa and Bambasi Districts, West Ethiopia. *Communications in Soil Science and Plant Analysis* 51(15): 1979-1990.

Baize, D. (1993). *Soil science analyses: a guide to current use*. John Wiley & Sons Ltd.

Bray, R. H. and Kurtz, L. T. (1945). Determination of total organic and available forms of phosphorus in soils. *Soil Science* 59: 39-45.

Brady, N. C., Weil, R. R., & Weil, R. R. (2008). *The nature and properties of soils* (Vol. 13, pp. 662-710). Upper Saddle River, NJ: Prentice Hall.

Bremner, J. M. (1982). Total nitrogen. In: *Methods of Soil Analysis*. *Part 2* Black *et al.* (Eds) Agronomy Monograph 9, American Society of Agronomy, Madison, Wisconsin, USA. pp. 1149-1170.

Buekers, J. and Jurgen (2007). *Fixation of Cadmium, Copper, Nickel and Zinc in Soil: Kinetics, Mechanisms and Its Effect on Metal Bioavailability*.PhD Thesis, Katholieke Universiteit Lueven, Dissertationes De Agricultura. 221pp.

Chapman, H. D. (1965). Total exchangeable bases. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties* 9: 902-904.

Chen, H., Liu, Y., Lü, L., Yuan, L., Jia, J., Chen, X. and Chi, G. (2021). Effects of no-tillage and stover mulching on the transformation and utilization of chemical fertilizer N in Northeast China. *Soil and Tillage Research* 213: 105131.

Dai, H., Wei, S., Skuza, L. and Jia, G. (2019). Selenium spiked in soil promoted zinc accumulation of Chinese cabbage and improved its antioxidant system and lipid peroxidation. *Ecotoxicology and environmental safety,* 180: 179-184. researchgate.net › publication › 28360305_ site visited on 12/08/2021.

Fernández, F. G. and Robert, G. Hoeft. (2009). Managing soil pH and crop nutrients. *Illinois Agronomy Handbook* 24: 91-112.

Food Agricultural Organization of the United Nations (FAO), (2006). *Guidelines for Soil Description.* 4th Edition. Food and Agriculture Organization of the United Nations, Rome, Italy. 66pp.

Food and Agriculture Organization of the United Nations (FAO), (2000). Fertilizers and their use. In: *International Fertilizer Industry Association*. 4th Edition. Rome, Italy. 70pp.

Giller, K. E. (2001). Targeting management of organic resources and mineral fertilizers: can we match scientists' fantasies with farmers' realities?. In *Integrated plant nutrient management in sub-Saharan Africa: From concept to practice* (pp. 155-171). Wallingford UK: CABI Publishing.

Gidago, G., Beyene, S., Worku, W. and Sodo, E. (2011). The response of haricot bean (*Phaseolus vulgaris* L.) to phosphorus application on Ultisols at Areka, Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare* 1(3): 38-49.

Gupta, S., Munyankusi, E., Moncrief, J., Zvomuya, F., & Hanewall, M. (2004). Tillage and manure application effects on mineral nitrogen leaching from seasonally frozen soils. *Journal of Environmental Quality* 33(4): 1238-1246.

Havlin, J. L., Beaton, J. D., Tisdale, S. L. and Nelson, W. L. (1999). *Soil Fertility and Fertilizers*, 6th Edition. Upper Saddle River, N.J.: Prentice Hall. 499pp.

Hodges, S. C. (2007). *Soil Fertility Basics.* Soil Science Extension North Carolina State University. 75pp.

Imakumbili, M. L., Semu, E., Semoka, J. M., Abass, A. and Mkamilo, G. (2019). Soil nutrient adequacy for optimal cassava growth, implications on cyanogenic glucoside production: A case of konzo-affected Mtwara region, Tanzania. *PLoS One* 14(5): e0216708.

Itanna, F. (2005). Sulfur distribution in five Ethiopian Rift Valley soils under humid and semi-arid climate. *Journal of Arid Environments* 62(4): 597-612.

Karlen, D. L., Varvel, G. A., Bullock, D. G. and Cruse, R. M. (2002). Crop rotations for the 21st century. *Advances in Agronomy* 53: 1–45.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V. and Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems and Environment* 229: 1-12.

Koskikala, J., Kisanga, D. and Käyhkö, N. (2020). Biophysical regions of the Southern Highlands, Tanzania: regionalization in a data scarce environment with open geospatial data and statistical methods. *Journal of Maps* 16(2): 376-387.

Kyveryga, P. M., Blackmer, A. M. and Zhang, J. (2009). Characterizing and classifying variability in corn yield response to nitrogen fertilization on subfield and field scales. *Agronomy Journal* 101: 269–277.

Landon,J. R. (1991). *Booker Tropical Soil Manual.* A handbook for soil survey and agricultural land evaluation in the tropics and subtropics, Longman Scientific and Technical Publishers, Essex. 474pp.

Libutti, C. M. (2018). Risk assessment of soil salinization due to tomato cultivation in Mediterranean climate conditions. *Water* 10(11): 1-19.

Lindsay, W. L., & Novell, W. A. (1978). Development of a DTPA soil test for zinc, iron, managancese, Litz, RE 2000. *Botany, Production and CABI. UK*, pp184-185.

Loria, E. R. and Sawyer, J. E. (2005). Extractable soil phosphorus and inorganic nitrogen following application of raw and anaerobically digested swine manure. *Agronomy Journal* 97(3): 879-885.

Mabagala, F. S. (2022). On the Tropical Soils; The Influence of Organic Matter (OM) on Phosphate Bioavailability. *Saudi Journal of Biological Sciences* 29(5): 3635-3641.

Marandu, A. E. T., Mbogoni, J. D. J. and Ley, G. J. (2014). Revised fertilizer recommendations for maize and rice in the Eastern, Southern highlands and Lake Zones of Tanzania. *Dar-es-Salaam: Ministry of Agriculture, Food Security and Cooperatives, Department of Research and Development*. 40pp.

Mardamootoo, T., Du Preez, C. C. and Barnard, J. H. (2021). Phosphorus management issues for crop production: A review. *African Journal of Agricultural Research* 17(7): 939-952.

McLean, F. B. and Oldham, T. R. (1982). Charge funneling in N-and P-type Si substrates. *IEEE Transactions on Nuclear Science* 29(6): 2017-2023.

Meliyo, J. L., Masuki, K. F. G., Kashenge-Killenga, S., Mbogoni, J. D. J., Mwango, S. H., Senkoro, C. J. and Kajiru, G. J. 6. Variability of exchangeable potassium in soils of Tanzania: A soil fertility challenge for sustainable crop production.

Merumba, S. M., Semoka, J. M. and Msanya, B. M. (2020). Soil Fertility Status in Bukoba, Missenyi and Biharamulo Districts in Kagera Region, Tanzania. *International Journal of Applied Agricultural Sciences* 6(5): 96-117.

Mkoma, A. (2015). *Response of maize to phosphorus in sole maize and maize-pigeonpea cropping system in semi-arid areas of Tanzania.* Doctoral Dissertation, for Award Degree at University of Dodoma. 96pp.

Moberg, J. P. (2001). *Soil Analysis Manual* (revised edition). The Royal Veterinary and Agricultural University. Chemistry Department, Copenhagen, Denmark. 137.

Moswetsi, G., Fanadzo, M. and Ncube, B. (2017). Cropping systems and agronomic management practices in smallholder farms in South Africa: constraints, challenges and opportunities. *Journal of Agronomy*16: 51–64.

Mowo, J. G., Floor, J., Kaihurm, F. B. S. and Magoggo, J. P. (1993). Review of Fertilizer Recommendations in Tanzania Part 2. *National Soil Services Report F*, *9,* 116pp.

Msanya, B. M., Kimaro, D. N., Mbogoni, J. D. J. and Kimbi, G. G. (2000). *Soils and Land Resources Report of Morogoro Urban District, Tanzania.* Sokoine University of Agriculture, Faculty of Agriculture, Department of Soil Science, Morogoro, Tanzania. Ministry of Agriculture, ARI- Mlingano, National Soil Service, Tanga, Tanzania. 78pp.

Msanya, B. M., Mwasyika, T. A., Amuri, N., Semu, E. and Mhoro, L. (2018). Pedological characterization of typical soils of Dodoma Capital City District, Tanzania: soil morphology, physico-chemical properties, classification and soil fertility trends. *Annals of Advanced Agricultural Sciences* 2(4): 59-73.

Msanya, K., Otsuka, A. and Pedological, N. (2003). characteristics, general fertility and classification of some benchmark soils of Morogoro District, Tanzania.

African Journal of Science and Technology, Science and Engineering Series 4(2): 101-112.

Murphy, J. and Riley, J. P. (1962). Modified single solution method for determination of phosphate in natural waters. *Analytica Chimica Acta.* 27: 31-36.

Mwenda, B., Kiambi, D., Kungu, J., Van De Gevel, J., Farda, C. and Morimoto, Y. (2020). Seasonal climate dynamics, perceptions and multiple risk adaptations: Lessons from Smallholder mixed agro ecosystems in Semi-arid Kenya. *Journal of Agricultural Extension and Rural Development*, 12(3): 76–90.

Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science* 2019: 1-9.

Nelson, D. W. and Sommers, L. E. (1982). Total carbon, organic carbon and organic matter. In: *Methods of Soil Analysis*. Part 2. 2nd Ed. (eds. Page, A. L, Miller, R. H., Keeney, D. R.) American society of agronomy, SSSA Monograph No. 9, Madison, Wisconsin, USA. pp539-579.

Nweke, I. A. and Ilo, G. E. (2019). Cultivation and land use changes their implications in soil productivity management and crop yield. *Journal of Agriculture and Agribusiness* 4(1): 35-62.

Okalebo, J. R., Gathua, K. W and Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis:* A working manual. 2nd Edition. TSBF-CIAT and SACRED Africa Nairobi. 127pp.

Ram, D., Ali, T., Mehraj, S., Wani, S. A., Jan, R., Jan, R. and Bhat, S. J. A. (2017). Strategy for optimization of higher productivity and quality in field crops through micronutrients: A review. *Economic Affairs* 62(1): 139-147.

Rhoades, J. D. (1982). Cation Exchange Capacity. In: *Methods of Soil Analysis*. (Edited by Page, A. L., Miller, R. H. and Keeney, D. R.), American society of Agronomy Inc., Madison, Wisconsin. pp. 149-157.

Robertson, G. P., Sollins, P., Ellis, B. G. and Lajtha, K. (1999). Exchangeable ions, pH, and cation exchange capacity. In: Robertson, G. Philip, Coleman, David C., Bledsoe, Caroline S., Sollins, Phillip, eds. *Standard soil methods for long-term ecological research*. New York, NY: Oxford University Press.pp106-114.

Rossi, J. (2009). Soil Organic Carbon in the Soil Scapes of South-eastern Tanzania. PhD thesis K.U. Leuven University, Belgium. [https://lirias.kuleuven.be › retrievePDF] site visited on 12/09/2021.

Rurinda, J., Zingore, S., Jibrin, J. M., Balemi, T., Masuki, K., Andersson, J. A. and Craufurd, P. Q. (2020). Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa. *Agricultural Systems* 180: 1-11.

Sanginga, N. and Woomer, P. L. (eds.) (2009). *Integrated Soil Fertility Management in Africa: Principles, Practices and Development Process.* Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture. Nairobi, Kenya. 263pp.

Scherer, H. W. (2001). Sulphur in crop production. *European Journal of Agronomy* 14(2): 81-111.

Stockdale, E. A., Shepherd, M. A., Fortune, S. and Cuttle, S. P. (2002). Soil fertility in organic farming systems–fundamentally different? *Soil Use and Management* 18: 301-308.

Thomas, G. W. (1986). Exchangeable cations. In: *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties.* 2nd Edition. Page, A. L., Miller, R. H., Keeney, D. R., Baker, D. E., Roscoe E., Ellis, J. and Rhodes, J. D. (Eds). Madison, Wisconsin, USA. pp. 403-430.

Usuga, J., Rodríguez, T., Andrés, J., Alzate, M. and Tapias, Á. (2010). Estimation of carbon stocks in plants, soil and forest floor in different tropical forests. *Forest Ecology and Management* 260: 1906 - 1913.

Vanlauwe, B., Ramisch, J. J. and Sanginga, N. (2006). Integrated soil fertility management in Africa: From knowledge to implementation. *Biological Approaches to Sustainable Soil Systems* 113: 257-272.

Verheye, W. (2006). Management of agricultural land: chemical and fertility aspects. *Land use, land cover and soil sciences,.(Ed. WH Verheye)(UNESCO-EOLSS Publishers: Oxford, UK)*. 44pp.

Viscontia, F., Miguelde, J. P. and Rubioa, J. L. (2010). What information does the electrical conductivity of soil water extracts of 1 and 5 ratio (w/v) provide for soil salinity assessment of agricultural irrigated lands? *Geoderma* 154: 387–397.

CHAPTER THREE

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

Abstract

This study was conducted in Nghumbi and Mlali villages in Kongwa District in Dodoma region, Tanzania to assess effectiveness of phosphorus solubilizing bacteria (PSB) on enhancing availability of phosphorus locked up in insoluble Minjingu phosphate rock for maize crop (*Zea mays* L.) in slightly acid to neutral soils. Five farms at Nghumbi village and two at Mlali village were randomly selected for field trials based on their soil pH and limiting nutrients. The trials were replicated three times arranged using complete randomised block design. Treatments tested were the control, soil/site characteristics, PSB inoculum co-applied with different rates of Minjingu phosphate rock (MPR) (0 – 60 kg ha^{-1}) as basal fertilizer by placing under maize seed and covering with a thin soil layer. Data collected at harvest were biological yield, grain yield, straws P concentration, straw P uptake, and P use efficiency. Results indicated the fields' characteristics from Farm 2 in Nghumbihad the highest yield to other fields with significantly (*P*< 0.001) highest grain yield being 4.4 t ha^{-1}which is really good, biological yield of 5.6 t ha^{-1}, and Straw P uptake of 19.63 kg ha^{-1}. The main effect of PSB treatments indicated that using P or inoculant (M_1)had no significant effects on yield of both grain and straw due to bad weather (drought) in the experimental area. No significant (*P* =0.427) interaction effects on the measured variables were observed in all the trials. I from study recommend more research on PSB for more than one season in slightly acid to neutral soil before ascertaining the technology to farmers.

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

3.1 Introduction

Low soil fertility is a constraint to crop production and productivity on smallholder farming systems in the semi-arid tropics (Ndungu- Magiroi *et al*., 2017). Many people living in semi-arid regions sustain themselves mainly from agricultural activities. About 821 million people are dependent on agricultural production for food and generation of income through selling of surplus, which does not exceed 20% (United Nations, 2018; Nassary *et al*., 2020). Most soils in semi-arid tropics of Africa are highly weathered and characterized by low fertility status due to low use of external fertilizer inputs, frequent nutrient uptakes by the crop, nutrient depletion through harvest and removal of crop residues, and erosion by wind and surface run-off (Giller, 2001; Giller *et al*., 2021a,b). Unsustainable agricultural practices, lack of resources and nutrient underuse in sub-Saharan Africa have resulted in significant soil nutrient depletion, low crop yield and poverty, leaving many farm families in a scenario of vulnerability and food insecurity (Chianu and Mairura, 2011). Food insecurity is expected to be extensive as human population and environmental degradation activities are increasing. In Sub-Saharan Africa (SSA) the human population was around 1.24 billion people in 2010 and it is projected to reach 3.1 billion people by 2030 (Vollset *et al*., 2020; Giller *et al*., 2021a). The increase in population is highly realized in rural areas where food production is largely for subsistence hence increase in land-use exhaustion causing nutrient depletion in the farming systems (Amsalu *et al.,* 2007). One option to manage soil fertility involves replenishment of nutrients removed from the soil by crops, leaching and erosion (Hengl *et al.,* 2017), and this is possible only by applying fertilizers. Fertilizer application increases crop yield and counteracts nutrient deficiency in soils (Hengl *et al*., 2017).

Phosphorus (P) is the macronutrient that frequently limits plant growth and the final yield, together with other nutrient elements. As a plant matures, absorbed phosphorus is translocated into fruiting parts of the plant, where high energy requirements are needed for the formation of seeds. Phosphorus deficiencies in soils affect both seed development and normal crop maturity. Phosphorus is most frequently deficient in soils of tropical Africa and is a major limiting nutrient element to maize production in Tanzania. It was reported by Mkoma (2015) that Kongwa district faces the situation in low available P as observed in in acidic and alkaline soils. The low soil P is caused by inherently low P in parent material, high P fixation by iron and aluminium oxides in acid soils (Silesh *et al.*, 2022), and precipitation by calcium in alkaline soils (Adnan *et al*., 2017).

The use of phosphate rock (PR) such as Minjingu phosphate rock (MPR) as an alternative P source has received high attention since 1960s, including Tanzania (Anderson, 1993; Ikerra *et al*., 1994; Szilas, 2002). Previous research findings indicated superiority of MPR through residual effect to the subsequent crop in the field after first application (Ikerra *et al*., 2007). High residual and longer lasting effects are due to the continuous slow release of P from MPR. Several research works have reported on the ability of PR to releaseP but information on how pH affects its dissolution in soils is limited.

It is challenging to use PR for crop production underneutral (pH 6.6–7.3), and alkaline (pH >7.3) soils due to low or complete absence of solubilisation to release P for crop use. Anderson *et al.* (2018) reported that PR solubilises well at pH ranging from 4.9 to 5.5 and keep decreasing as soil pH increases to 6.2. Above soil pH of about 6.1 PR is completely insoluble. A study conducted by Bolan and Hedley (1990) using three types of PR namely Nauru PR (NPR), Jordan PR(JPR) and North Carolina PR (NCPR), showed that at each pH the order of the extent of PR dissolution followed the NCPR> JPR> NPR, which was consistent with the decreasing order of the chemical reactivities. As pH decreased from 6.5 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.

To enable the locked-up P in the insoluble PR when applied in high soil pH, an exploration of special mechanism is required. 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 acid (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). Furthermore, the bacteria also create acidity by evolution of carbon dioxide (CO_2) that in turn solubilises calcium phosphates (Yousefi *et al*., 2011). It has been proven that phosphorus solubilising bacteria increase P availability in soils of high (>6.2) pH and hence promotes crop growth (Bhattacharyya and Jha, 2012).

Maize yield was reported to increase when PSB were inoculated in metal polluted soils with alkaline pH (Jiang *et al.,* 2008). Linu *et al.* (2009) found that nodulation, root and shoot biomass of the maize and cowpea plants inoculated with *B. Cepacta* were significantly higher as compared to control at the pH of 8. While the benefits of bacteria in enhancing P availability from PR is widely documented (Zaidi *et al*., 2009) such studies are rarely reported in Tanzania. Little information available are elusive or inconclusive with no evidence of any study under neutral (6.7) to slight alkaline (7.7) soils. Therefore, the general objective of the study was to optimize maize production through increased P availability from Minjingu PR by combining phosphorus solubilizing bacteria (PSB) with MPR for conversion of insoluble PR to soluble and release P in slightly acid to neutral soils in selected villages of Kongwa district, Dodoma region. The specific objectives were to determine effectiveness of PSB on solubilizing MPR and its effects on maize yield, and determine effects of field characteristics on maize performance because fields used in the study varied widely in nutrient composition.

3.2 Materials and Methods

3.2.1 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.

Kongwa district has undulating to rolling plains and plateaux with an altitude ranging from 700 to 900 metres above sea level (masl). Rains are usually unpredictable with variability in their onset, distribution, and intensity (Lymo *et al.,* 2013). The study area has 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).

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).

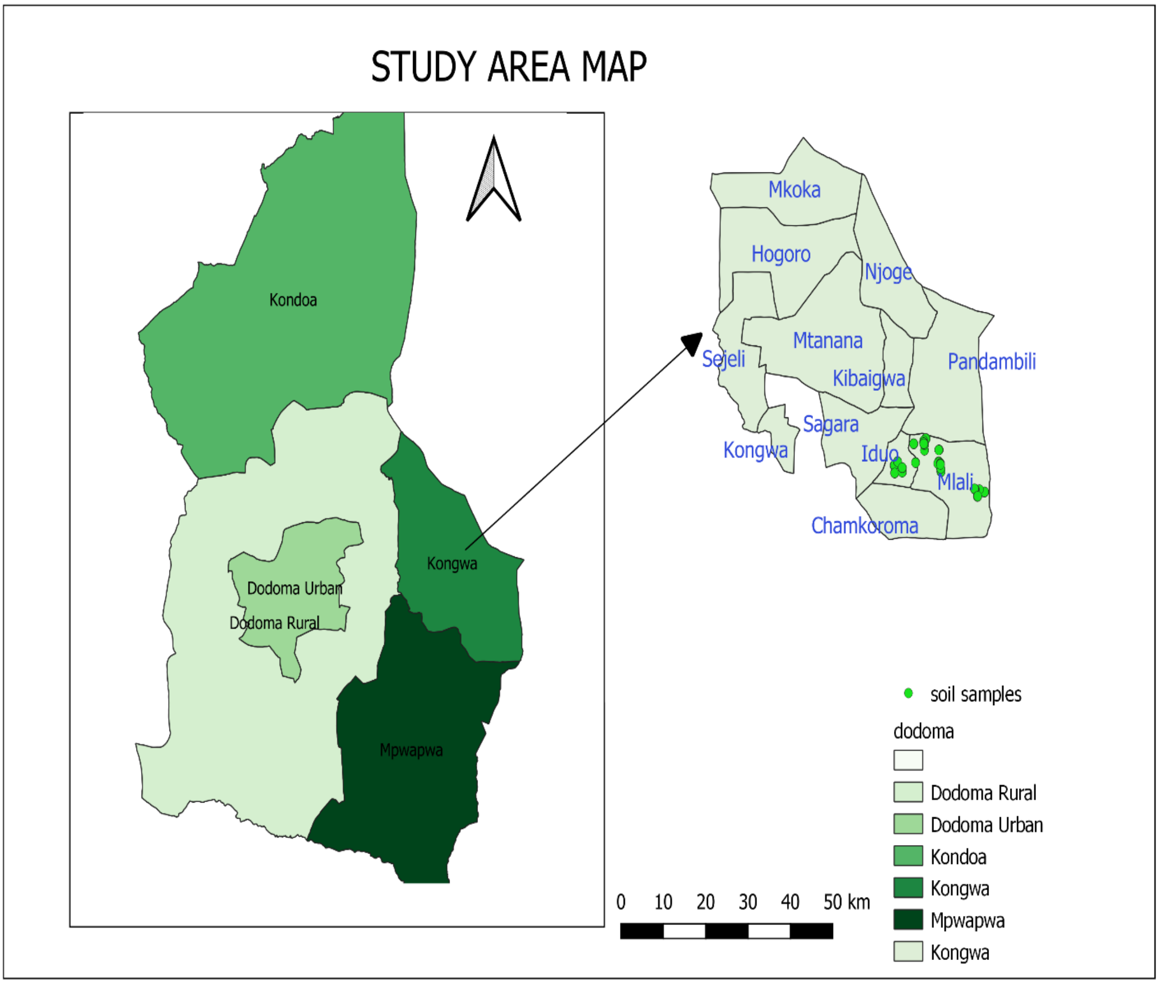

Figure 3.1: Map of Dodoma region showing study district and villages in which experiments were conducted

3.2.2 Site selection for the study

A reconnaissance visit was conducted in seven important maize growing areas in Kongwa district to establish the cropping history of the fields as well as understanding practices of maize production including varieties used, planting dates and setting up of a growing season. Also, consultative meetings and focus group discussions (FGDs) with village leaders and individual farmer were conducted. Seven fields (two at Mlali and five at Nghumbi) with the desired soil pH in the study area were selected. Soil data showing the fertility status of the selected fields were extracted from chapter two. The fields had a soil pH ranging from neutral to slightly alkaline), soils were reddish to greyish, and dominated by sandy loam texture. Limiting nutrients for each studied field were identified and sorted so as to understand the field characteristics and specific nutrients that are likely to limit crop growth and development. Soil data from chapter two were used to evaluate field characteristics and limiting nutrients of each field and this information is summarized in Table 3.3.

3.2.3 Inoculant used

The inoculum was obtained ready made by Kwaslema, (2021 and preserved in Soil Microbiology laboratory in the Department of Soil and Geological Sciences at the Sokoine University of Agriculture. Bacteria inoculum in liquid form contained 10^9 cells per mL. The inoculum was diluted in 1: 20 (inoculum: water), then 5 mL (5^6 cells in 5 mL) was applied per hole. Names of microbial composition from various crops were used in this study (source: SUA soil laboratory) are shown in Table 3.1.

Table 3.1: Identity of isolated PR-solubilizing species based on nucleotide database on American National Institute of Health (NIH) NCBI genetic database (GenBnk).

Isolate	Species	Accession number	Nucleotide identity	Country	Source rhizosphere
Fg1	*Fusarium proliferatum*	MZ497514	100	Tanzania	Maize
Mk10	*Burkholderia sp*	MZ502221	99.9	Tanzania	Maize
NA19a	*Klebsiella sp*	MZ502673	99.9	Tanzania	Maize
Klm3	*Burkholderia sp*	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

Source: Kwaslema, 2021.

3.2.4 Experimental design, treatments and field experimentation

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. Treatment one (T1) was a treatment control in which neither P nor phosphorus solubilizing bacteria (PSB) was applied (P_0M_0); Treatment two (T2) was treated with P from Minjingu phosphate rock (MPR) at recommended rate (30 kgha^{-1}) ($P_{30}M_0$); Treatment three(T3), received only PSB (P_0M_1); Treatment four (T4) was treated with Minjingu fertilizer at the rate of 20 kg P ha^{-1} plus PSB ($P_{20}M_1$); Treatment five (T5) was treated with Minjingu fertilizer at the rate of 40 kg P ha^{-1} plus PSB ($P_{40}M_1$); Treatment six (T6) received both Minjingu fertilizer at the rate of 60 P ha^{-1} and PSB ($P_{60}M_1$). Farmer's fields were treated as fixed effects because they varied widely in nutrient composition. The treatments except for soil characteristics, were replicated three times giving a total of eighteen plots. The study adopted a randomized complete block design (RCBD) with maize as a test crop. Each experimental plot was 4 m in length and 3 m in width = 12 m^2.

Two maize seeds (*variety Situka*) were sown per hole from 25th to 30th of November, 2020/21 and there were four rows and 13 holes in a row since the spacing was 90 cm between rows and 30 cm within rows.. The P fertilizers were applied by placing under maize seed and covering with a thin soil layer. The inoculum at 5 mL of solution was applied to each planting hole3 days after emergency. Limiting nutrients such as N and S were corrected by applying Urea with S (N 40% and S5.5%) brand Yara Amidas.

3.2.5 Management of the field experiment

This involved the collection and removal of previous crop residues, grasses and weeds from the field on which maize was previously cultivated. Land preparation was done two weeks before planting which was done by conventional tillage system by tractor and levelling was done by hand hoe. Thinning of maize seedlings was done two weeks after emergence, leaving two plants per hill. Hand hoe weeding was done two times throughout the season to make sure that the field remained weed free. Fall army worms were controlled by spraying an insecticide called Sulphur 80 Wg (active ingredient is S).

3.2.6 Data collection

3.2.6.1 Rainfall information in the study area

The information on rainfall was collected daily from November 2020 to April 2021 from the rainfall station installed in the experimental area (closest to Loti field) by USAID through IITA -Africa RISING ESA Project in 2019. There was none linear (polynomial) decrease in rainfall during the period when maize plants were in the experimental fields. Evapotranspiration data were collected from the closest experimental site for collection of evapotranspiration conducted by Casper (2002).

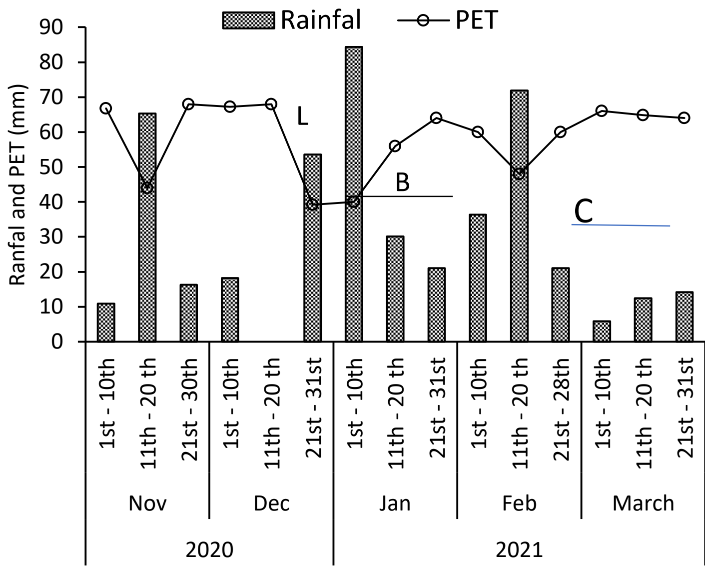

Figure 3.2: Trends of rainfall (mm) and Evapotranspiration in the study area during period of experimentation (2020/2021) with maize crop – Kongwa district. L = shows the planting date, B = is the drought period during vegetative growth, C = drought period during flowering and grain filling.

3.2.6.3 Laboratory analysis of plant samples

Fully matured maize plants were harvested from each plot and separately weighed to obtain biomass, and cobs were threshed and weight of dry grains determined. The cobs and straws were cleaned, chopped and processed in the laboratory for analysis of P concentrations as described by Moberg (2002). The plant sample was oven dried for overnight and then heated in the muffle furnace for about 5 hours. The ash was cooled and digested with 20 percent nitric acid and filtered using Whiteman filter paper and finally made into a yellow phospho-vanadate complex liquid, from which Phosphorus was determined colorimetric ally (Moberg, 2002).

P uptake and P use efficiency was calculated. Thereafter, P uptake by maize straw was calculated using the formula in Equation 1.

$$\text{P uptake (kg ha}^{-1}) = \text{P conc. in straw (\%)} \times \text{straw yield (kg ha}^{-1}) \times 10 \qquad (1)$$

P uptake by straw was determined using biological yield obtained per unit of nutrient uptake as shown in Equation 2.

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

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 straw/uptake and maize biomass yield as shown in Equation 3.

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

3.2.7 Statistical analysis

Data collected i.e. phosphorus concentration (% P), total P uptake, P use efficiency, biological yield, and grain yield were subjected to TWO–WAY analysis of variance (ANOVA) and the model is in Equation 4. Fixed effects i.e. the field characteristics were treated so since they had different nutrient composition and therefore it was crucial to separate them form main treatments i.e. PSB co-applied with MPR

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

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.

3.3 Results and Discussion

Limiting nutrients in the soils of experimental fields

Limiting nutrients in the soils of the studied fields were categorized and results are presented in Table 3.3 (Source: Chapter 2). Classification and rating of the nutrients was done according to individual chemical properties that are found in Chapter Two. It was realized that N, P, K, and Zn were the limiting nutrients in the soils of the experimental fields. Nitrogen (N) was limiting in all soils and was corrected by applying N containing fertilizer (Yara Amidas). Maize is the commonly cultivated food crop by smallholder farmers in the study area but its optimum yield has not been achieved due to poor soil fertility which is a result of low or no external nutrient inputs.

Table 3.2: Limiting nutrients in each of the selected fields in the studied fields in Kongwa district

Village	Coordinates		Owner	Farm No.	Soil pH_{H2O}	Limiting nutrients
Nghumbi	S 06.31561	E 036.82605	Timoth	1	7.05	N
	S 06.31456	E 036.82698	Lot	2	7.06	N
	S 06.31414	E 036.84106	Dadili	3	7.1	N
	S 06.30932	E 036.83009	Mary	4	6.69	N
	S 06.30815	E 036.81939	Luka	5	6.99	N and K
Mlali	S 06.26317	E 036.74073	Joshua	1	7.22	N, P, Zn and K
	S 06.26348	E 036.74657	Eva	2	7.63	N, P, Zn and K

Source: Chapter two Table 2.3 and 2.4

3.4 Maize Performance in the Study fields

3.4.1 Effect of field characteristics

Maize parameters analysed were grain yield, P uptake, straw yield and P use efficiency (Table 3.4 and 3.5). Maize performance was assessed based on the individual field selection criteria such as soil pH and limiting nutrients identified across fields. The P concentration, P uptake, P use efficiency, biological yield, and grain yield were compared across fields using ANOVA, (Table 3.4 and 3.5). From the ANOVA table it is observed that the main treatment effect is insignificant at the *P*- value of < 0.001while the farmer's field characteristics significantly affected grain, biomass yield and P concentrations (Tables 3.4 and 3.5) at the *P*- value of <0.001.

Table 3.3: Analysis of variance (ANOVA) for P concentration, total P uptake, and P use efficiency in maize as affectedbyfarmer's field characteristics, treatments, and their interactions in Kongwa district

Source of variation	d.f	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	0.821587				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 3.4: Analysis of variance (ANOVA) for 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

Maize yield in the selected fields followed the sequence: Loti> Luka> Mary> Joshua> Timoth= Eva> Dadili. The main effect of field characteristics indicated that grain yield of maize from Lot's field was highest of all the fields with significantly difference (*P*< 0.001) from other fields as shown in the sequence above. The grain yield at Lot`s field was 4.0 t $ha^{-}$, (Table 3.6). The significant high yield at Loti`s field was probably caused by favourable soil characteristics since the soils had only one limiting nutrient, N (Table 3.3) which was as well corrected. The field had high native phosphorus which amounted to 53.4 mg kg^{-1}.

Table 3.5: P concentration, Straw P uptake, grain yield, biological yield and P use efficiency in maize as affected by farmer's field characteristics and PSB treatments in the study sites in Kongwa district.

Farmer's field	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})
Lot		4.0a	5.6a	0.12a	10.81 a	246.8bcd
Mary		2.6c	4.7ab	0.08ab	7.96ab	219.4cd
Timoth		1.8de	1.5e	0.08ab	2.38d	351.8a
Dadili		1.5e	3.0cd	0.10ab	5.18bcd	195.1d
Luka		3.3b	4.0bc	0.09ab	7.21abc	272.1bc
Eva		1.8de	2.2de	0.11a	4.03cd	294.8ab
Joshua		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_1	2.7a	3.6a	0.09a	6.59a	267.5a
	$P_{20}M_1$	2.4a	3.3a	0.07a	5.48a	271.5a
	$P_{40}M_1$	2.5a	3.8a	0.08a	7.05a	247a
	$P_{60}M_1$	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.

The second highest maize grain yield (3.3 t ha^{-1}) was recorded in Luka's field, where there were two limiting nutrients i.e., N and K from which N was corrected. The significantly lower yield at Luka`s field next to Lot could presumably be caused by slight limitation of K (0.21) which was close to moderate level as seen in chapter two (Przygocka *et al*., 2020). Yield in Luka`s field was followed by grain yields in Mary's (2.6 t ha^{-1}) and Joshua's (2.2 t ha^{-1}) fields. Mary`s field had only one limiting nutrient (N) while Joshua`s fields had four limiting nutrients i.e. N, P, K and Zn (Table 3.3). These limiting nutrients could be the main cause for low grain yield in Joshua`s field.

Also, low grain yields were recorded in Eva's and Timoth's fields (1.8 t ha^{-1}). Eva's field had four limiting nutrients (N, P, K and Zn) while Timoth's field had one limiting nutrient (N). The limiting nutrients in Eva's field are thought to be the reasons for low grain yield while Timoth's field low grain was probably caused by bad weather (drought). Dadili's field had the lowest grain yield (1.5 t ha^{-1}) and had a contrasting trend in that yield did not seem to relate to limiting 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 2020 to mid-February 2021 and during flowering to grain filling in March (Fig. 3.2). The periods where evapotranspiration was higher than rainfall experienced soil moisture stress.

Biological/straw yields followed the sequence: Lot > Mary> Luka>Joshua>Dadili>Eva>Timoth. This trend also falls in sequence and number of limiting nutrients observed in the fields as for the case in grain yield except for Dadili's field where low yield is thought to be due to inadequate soil moisture. These findings except for Dadili and Luka are consistent with those of field characteristics categorized based on the limiting nutrients. The P uptake results followed the trend Loti ≈ Mary ≈ Luka ≈ Joshua ≈ Dadili ≈ Eva ≈ Timoth. It has been proven and reported that most of the P in maize crop is concentrated in grains and this affects nutritional quality such as protein, starch and micronutrients (Wafula *et el*., 2018).

Phosphorus concentration in Loti's field was found to be 0.27% (Table 3.7). The critical concentration of P in maize straw is reported to be 0.26% by mass of which 60 to 80% is in the form of phytate (Wu *et al*., 2015). The P uptake ranging from 15 to 30 kg ha^{-1} is desirable in maize straw (Assefa *et al*., 2021). The slight high P concentration in Loti's field (i.e. 0.27%) is presumably due to high native P (53.5 mg kg^{-1}) in the soils which may have been taken up by plant in early stages of maize growth. This situation has also been observed in Luka's field from which the soil native P was sufficient (22.1 mg kg^{-1}) for maize growth. Fields with lower native P like those of Joshua and Eva (9.2 mg kg^{-1}) were found to have low P concentrations, 0.07 to 0.17% and 0.07 to 0.17%, respectively (Table 3.7). These findings corroborate Gomez- Munoz *et al*. (2018) that high native P increase yields in grain-based crops. Similar results of improved crop yields in soil with high native P are also reported by other researchers (e.g., Mehrvarz, 2008; Krey *et al*., 2013; Saleque *et al*., 2014; Leggett *et al*., 2015; Santana, 2016; Selvi, 2017; Raymond *et al*., 2019).

In addition to the results for maize grain yield, P use efficiency also differed significantly (P =0.003) across the fields but with no clear trend; these findings reflected heterogeneity in nutrient levels. The range of PUE in this study was between 195.1 to 351 kg kg^{-1}. A study by Baligar *et al*. (1990) reported very high ranges of PUE amounting from 400 to 500 kg kg^{-1}. The high PUE in study by Baligar *et al*. (2001) was due to conducive environment including enough soil moisture which supported proper functioning of PSB and eventually high plant uptake.

Comparing this range with those obtained in this study, it can be observed that PUE data are very low. The generally low levels of PUE are presumably caused by low dry matter yield which was due to drought experienced in the experimental site period (Chowdhury and Zhang, 2021. In this study PUE has been defined according to Baligar *et al*. (1998) who stated that dry matter yield (kg) divided by nutrient accumulation/uptake (kg) is one way to express phosphorus use efficiency in plants (Chen and Graedel, 2016). PUE is important in crop production systems since it acts as an indicator for measuring the status of P management in the agricultural production system and its impact on food security and environmental conservation.

3.4.2 PSB treatments effects on maize performance

Grain yield, biological yield, P concentration straw uptake and use efficiency data are presented in Table 3.6. The experimental treatment combinations in this study were the PSB inoculum co-applied with MPR at different rates. The PSB had no significant effect on grain yield, straw yield and P uptake in all the sites and the reasons are suggested to be, firstly: the P from MPR did not properly dissolve because of high soil pH and little soil moisture caused by drought experienced in the study site which began from three weeks after emergence and extended for about 35 days in November to 20th December (Fig. 3.2). Additionally, PSB as inoculum did not help much solubilization of P from MPR because of poor soil moisture.Low soil moisture reduces activeness of PSB, P diffusion in the soil and from the soil to plant roots (Widdig *et al*., 2019). With such a drought condition experienced in the field during vegetative stage, inoculum applied in the soil could not survive. Schutz *et al*. (2018) reported that phosphate solubilizing bacteria have greater effect with applied P fertilizer at rates ranging between 40 and 60 P kg P ha^{-1} in sufficient soil moisture.

Table 3.6 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 -field	Treatments	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})	P concentration (%)	Straw P uptake (kg ha^{-1})	P use efficiency (kg kg^{-1})
Dalali	P_0M_0	1.1	2.9	0.13	6.23	179.2
Dalali	$P_{20}M_0$	1.4	2.6	0.13	6.7	211.2
Dalali	P_0M_x	1.8	3.4	0.17	8.1	218
Dalali	$P_{20}M_1$	1.4	3.2	0.13	9.33	149.3
Dalali	$P_{40}M_1$	1.9	3.0	0.13	7.93	247.5
Dalali	$P_{60}M_1$	1.3	3.1	0.10	8	165.7
Timoth	P_0M_0	1.4	1.1	0.17	4.17	326.2
Timoth	$P_{20}M_0$	1.9	1.6	0.13	5.33	460.8
Timoth	P_0M_x	1.7	1.5	0.13	4.97	335.5
Timoth	$P_{20}M_1$	1.6	1.4	0.17	5.3	293.4
Timoth	$P_{40}M_1$	2.6	2.2	0.17	7.57	358.2
Timoth	$P_{60}M_1$	1.4	1.2	0.13	4.17	337
Mary	P_0M_0	2.9	4.6	0.13	12.93	235.1
Mary	$P_{20}M_0$	2.1	4.2	0.17	10.8	195.9
Mary	P_0M_x	2.8	5.3	0.17	14.07	202.3
Mary	$P_{20}M_1$	2.9	4.7	0.13	11.7	263.4
Mary	$P_{40}M_1$	2.4	5.0	0.20	11.73	226.4
Mary	$P_{60}M_1$	2.7	4.6	0.17	13.73	193.2
Luka	P_0M_0	3.0	4.2	0.20	14.4	215.1
Luka	$P_{20}M_0$	3.2	3.6	0.17	12	293.2
Luka	P_0M_x	3.9	4.8	0.20	14.93	261.3
Luka	$P_{20}M_1$	3.4	3.3	0.13	10.27	329.4
Luka	$P_{40}M_1$	2.4	4.2	0.17	13.63	201.1
Luka	$P_{60}M_1$	4.2	3.9	0.17	13.27	332.7
Lot	P_0M_0	4.2	6.0	0.20	17.37	248.6
Lot	$P_{20}M_0$	3.6	4.5	0.20	13.2	307.7
Lot	P_0M_1	4.4	5.1	0.27	18.13	257
Lot	$P_{20}M_1$	3.7	5.7	0.20	16.93	225.1
Lot	$P_{40}M_1$	3.9	5.6	0.23	19.63	213
Lot	$P_{60}M_1$	3.8	6.8	0.20	17.23	229.3
	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.

Table 3.7: 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-based-field	Treatments	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})	P concentration (%)	Straw P uptake (kg ha^{-1})	P use efficiency (kg kg^{-1})
Joshua	P_0M_0	1.9	2.3	0.13	6.1	317.1
Joshua	$P_{20}M_0$	2.4	4.1	0.13	11.87	220.2
Joshua	P_0M_1	2.3	2.5	0.10	7.37	318.7
Joshua	$P_{20}M_1$	2.1	3.3	0.07	7.17	317.3
Joshua	$P_{40}M_1$	2.7	5.6	0.13	13.77	233.7
Joshua	$P_{60}M_1$	2.0	2.6	0.17	8.27	369.9
Eva	P_0M_0	1.6	3.4	0.10	7.27	273.5
Eva	$P_{20}M_0$	2.1	3.0	0.13	9.07	275
Eva	P_0M_1	2.2	2.4	0.17	10.67	279.9
Eva	$P_{20}M_1$	1.7	1.6	0.17	5.3	322.4
Eva	$P_{40}M_1$	1.5	1.2	0.17	7.9	249
Eva	$P_{60}M_1$	1.7	1.8	0.07	4.83	369.2
	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.

There were no significant (*P* =0.427) interaction effects of field characteristics and PSB on the measured variables, but grain yields were slightly higher in Lot's field with P_0M_1 (4.4 t ha^{-1}) than in $P_{40}M_1$ (3.9 t ha^{-1}) treatments (Table 3.6 and 3.7). Under this observation and tailored to the previous results recorded in the main effect of treatment, native P was the main source of P in the crops and not the supplied MPR and inoculant combinations. These findings suggest that the performance of maize in the study area is dependent on the soil nutrient status especially P, N, and K. Interaction effects provide an interesting insight that maize response to native P inputs in the study area is a factor of soil and amount of P applied or released to the soil. These findings are in line with those reported by Frossard *et al*. (2000) that crop performance is dependent on the number of factors including diverse soil characteristics

3.5 Conclusions and Recommendations

The main effect of fields' characteristics indicated that performance of maize in Lot's field was statistically the highest of all other fields with highest grain yield, biological yield, and total P uptake. Furthermore, the P use efficiency also differed significantly across the fields reflecting heterogeneity in nutrient levels. The main effect of PSB treatments indicated that use of P or inoculants separately did not result into promising grain yield increment. Although there were no significant interaction effects of field characteristics and treatment combination on the measured variables in maize, grain yields were significantly higher in Lot's field than in other fields due to its high native P in soils. These findings suggest that the performance of maize in the study area is dependent on the soil nutrient status (especially N, and K) and native P.

It is recommended that, more field trials using more than one season is needed to ascertain the significance of solubilizing bacteria in enhancing P availability from MPR for improvement of maize productivity before the technology is recommended for farmer's adoption.

References

Adnan, M., Shah, Z., Fahad, S., Arif, M., Alam, M., Khan, I. A. and Nasim, W. (2017). Phosphate-solubilizing bacteria nullify the antagonistic effect of soil calcification on bioavailability of phosphorus in alkaline soils. *Scientific Reports* 7(1): 1-13.

Amsalu, A., Stroosnijder, L. and de Graaff, J. (2007). Long-term dynamics in land resource use and the driving forces in the Beressa watershed, highlands of Ethiopia. *Journal of Environmental Management* 83(4): 448-459.

Anderson, J. M. and Ingram, J. S. I. (1993). *A Handbook on Methods of Soil Analysis, 2nd edition.* Tropical Soil Biology and Fertility (TSBF), CABI, Wallingford. 140pp.

Assefa, S., Haile, W. and Tena, W. (2021). Effects of phosphorus and sulfur on yield and nutrient uptake of wheat (*Triticum aestivum* L.) on Vertisols, North Central, Ethiopia. *Heliyon* 7(3): e06614.

Baligar, V. C., Duncan, R. R. and Fageria, N. K. (1990). Soil-plant interaction on nutrient use efficiency in plants: An overview. In: *Baligar, V. C. and Duncan, R.* (*eds.*), *Crops as Enhancers of Nutrient Use.* Academic Press, San Diego, CA.pp. 351–373.

Baligar, V. C., Fageria, N. K. and Elrashidi, M. A. (1998). Toxicity and nutrient constraints in root growth. *Horticultural Science* 36: 960–965.

Baligar, V. C., N. K. Fageria, and Z. L. He. 2001. Nutrient use efficiency in plants. *Communications in Soil Science and Plant Analysis* 32: 921–950.

Bhattacharyya, P. N., Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. *World Journal Microbiol Biotechnol* 28(4): 1327–50.

Bolan, N. S. and Hedley, M. J. (1990). Dissolution of phosphate rocks in soils. 1. Evaluation of extraction methods for the measurement of phosphate rock dissolution. *Fertilizer Research* 19(2): 65-75.

Brady, N. C. and Weil, R. R. (2017). *The Nature and Properties of Soils.* 15th Edition. Pearson Education. Essex, England. 1104pp.

Chen, M. and Graedel, T. E. (2016). A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts Global. *Environmental Change* 36(2016): 139-152.

Chianu, J., Chianu, J. and Mairura, F. (2011). Mineral fertilizers in the farming systems of subSaharan Africa. A review. *Agronomy for Sustainable Development* 32: 1-11.

Chowdhury, R. B. and Zhang, X. (2021). Phosphorus use efficiency in agricultural systems: A comprehensive assessment through the review of national scale substance flow analyses. *Ecological Indicators* 121: 107172.

Fischer, K. S. (1998). Toward increasing nutrient use efficiency in rice cropping systems: the next generation of technology. *Field Crops Research* 56:1–6.

Giller, K. E. (2001). *Nitrogen Fixation in Tropical Cropping Systems*, 2ndedn. CAB International, Wallingford, UK. 297pp.

Giller, K. E., Delaune, T., Silva, J. V., Descheemaeker, K., van de Ven, G., Schut, A. G. T., van Wijk, M., Hammond, J., Hochman, Z., Taulya, G., Chikowo, R., Narayanan, S., Kishore, A., Bresciani, F., Teixeira, H. M., Andersson, J. and Van Ittersum, M. K. (2021a). The future of farming: Who will produce our food? *Food Security* 13: 1073-1099.

Giller, K. E., Delaune, T., Silva, J. V., Descheemaeker, K., van de Ven, G., Schut, A. G. T., van Wijk, M., Hammond, J., Taulya, G., Chikowo, R. and Andersson, J. (2021b). Small farms and development in sub-Saharan Africa: Farming for food, for income or for lack of better options? *Food Security*13: 1431–1454.

Gomez-Munoz, B., Jensen, L., de Neergaard, A., Richardson, A. and Magid, J. (2018). Effects of *Penicillium bilaii* on maize growth are mediated by available phosphorus. *Plant and Soil* 431: 159–173.

Gupta, R. P. and Mishra, B.(1978). Phosphorus availability from rock phosphate as influenced by pyrite, wheat straw and superphosphate to, maize-clover on a Mollisol. *Acta Agronomica* 27:126-132.

Hansen, V., Bonnichsen, L., Nunes, I., Sexlinger, K., Lopez, S. R., van der Bom, F. J. T., Nybroe, O., Nicolaisen, M. H. and Jensen, L. S. (2020). Seed inoculation with *Penicilliumbilaiae* and Bacillus simplex affects the nutrient status of winter wheat. *Biology and Fertility of Soils* 56: 97–109.

Hengl, T., Leenaars, J.G.B., Shepherd, K.D., Walsh, M.G., Heuvelink, G. B. M., Mamo, T. and Tilahun, H. (2017). Soil nutrient maps of subSaharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. *Nutrient Cycling in Agroecosystems* 109(1): 77–102.

Ikerra, S. T., Semu, E. and Mrema, J. P. (2007). Combining Tithonia diversifolia and minjingu phosphate rock for improvement of P availability and maize grain yields on a chromic acrisol in Morogoro, Tanzania. In: *Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities*. Springer, Dordrecht. pp. 333-344.

Jiang, C., Sheng, X., Qian, M. and Wang, Q. (2008). Isolation and characterization of a heavy metal-contaminated paddy field soil and its potential in promoting plant growth and heavy metal accumulation in metal-polluted soil. *Chemosphere* 72(2): 157-164.

Kimaro, A. A., Timmer, V. R., Chamshama, S. A. O., Ngaga, Y. N. and Kimaro, D. A. (2009). Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops. *Agriculture, Ecosystems & Environment* 134(1-2): 115-125.

Krey, T., Vassilev, N., Baum, C. and Eichler-Löbermann, B. (2013). Effects of long-term phosphorus application and plant-growth promoting rhizobacteria on maize phosphorus nutrition under field conditions. *European Journal of Soil Biology* 55: 124-130.

Kwaslema, D. R. (2021). *Potential of phosphate solubilising bacteria for enhancing Minjingu rock-phosphate solubility and phosphorus-use efficiency for sustainable maize production in acid soils*. Doctoral Dissertation for Award Degree at Sokoine University of Agriculture. 187pp.

Leggett, M., Newlands, N., Greenshields, D., West, L., Inman, S. and Koivunen, M. (2015).Maize yield response to a phosphorus-solubilizing microbial inoculant in field trials. *Agriculture Science*153(8):1464-1478.

Linu, M., Stephen, J. and Jisha, M. (2009). Phosphate solubilizing Gluconacetobacter sp., Burkholderiasp. and their potential interaction with cowpea (*Vigna unguiculata* (L.) Walp.). *International Journal of Agriculture Research* 4(2): 79–87.

Lyimo, J. G., Ngana, J. O., Liwenga, E. and Maganga, F. (2013). Climate change, impacts and adaptations in the coastal communities in Bagamoyo District, Tanzania. *Environmental Economics* 4(1): 63-71.

Mehrvarz, M.,Chaichi, R. and Alikhani, H. A. (2008). Effects of phosphate solubilizing microorganisms and phosphorus chemical fertilizer on yield and yield components of barely (*hordeum vulgare L*.), *American-Eurasian Journal of Agricultural and Environmental Science* 3: 822–828.

Meliyo, J. L., Masuki, K. F. G., Kashenge-Killenga, S., Mbogoni, J. D. J., Mwango, S. H., Senkoro, C. J., ... & Kajiru, G. J. (2014). Variability of exchangeable potassium in soils of Tanzania: A soil fertility challenge for sustainable crop production. 6pp.

Mkoma, A. (2015). *Response of maize to phosphorus in sole maize and maize-pigeonpea cropping system in semi-arid areas of Tanzania*. M.Sc. Dissertation for Award Degree of Master of Science in Soil Science and Land Management of Sokoine University of Agriculture. Morogoro, Tanzania. 68pp.

Moberg, J. P. (2001). *Soil Analysis Manual* (revised edition). The Royal Veterinary and Agricultural University. Chemistry Department, Copenhagen, Denmark. 137.

Nassary, E. K., Baijukya, F. and Ndakidemi, P. A. (2020). Assessing the productivity of common bean in intercrop with maize across agro-ecological zones of smallholder farms in the northern highlands of Tanzania. *Agriculture* 10(4): 1-15.

Ndungu-Magiroi, K. W., Kasozi, A., Kaizzi, K. C., Mwangi, T., Koech, M., Kibunja, C. N. and Wortmann, C. S. (2017). Finger millet response to nitrogen, phosphorus and potassium in Kenya and Uganda. *Nutrient Cycling in Agroecosystems* 108: 297-308.

Olsen, S. R., Kemper, W. D. and Van Schaik, J. C. (1965). Self-diffusion coefficients of phosphorus in soil measured by transient and steady state methods. *Soil Science Society of America Journal* 29(2): 154–158.

Osorio, N. W. (2008). *Effectiveness of microbial solubilization of phosphate in enhancing plant phosphate uptake in tropical soils and assessment of the mechanisms of solubilization*. Ph.D. Thesis, University of Hawaii, Honolulu. [https://www.scielo.sa.cr › scielo] site visitedon 15/09/2021.

Pradhan, N. and Sukla, L. B. (2005). Solubilization of inorganic phosphate by fungi isolated from agriculture soil, *African Journal of Biotechnology*, vol. 5, pp.

Przygocka-Cyna, K. and Grzebisz, W. (2020). The multifactorial effect of digestate on the availability of soil elements and grain yield and its mineral profile. The case of maize. *Agronomy* 10(2): 850–854.

Raymond, N. S., Jensen, L. S. and St€over, D. M. (2018). Enhancing the phosphorus bioavailability of thermally converted sewage sludge by phosphate-solubilising fungi. *Ecological Engineering* 120: 44–53.

Saleque, M. A., Abedin, M. J., Ahmed, Z. U., Hasan, M. and Panaullah, G. M. (2001). Influences of phosphorus deficiency on the uptake of nitrogen, potassium, calcium, magnesium, sulfur, and zinc in lowland rice varieties. *Journal of Plant Nutrition* 24: 1621–1632.

Santana, E. L., Marques, S. and Dias, J. C. T. (2016). Effects of phosphate-solubilizing bacteria, native microorganisms and rock dust on *Jatropha curcas* L. growth, *Genetics and Molecular Research*, vol. 15, no. 4.

.Schutz, L., Gattinger, A., Meier, M., Muller, A., Boller, T., Mader, P. and Mathimaran, N. (2018). Improving crop yield and nutrient use efficiency via biofertilization – Aglobal meta-analysis. *Frontiers in Plant Science* 8: 1-13.

Selvi, J. J., Paul, A., Vijaya, V. and Saraswathi, K. (2017). Analyzing the efficacy of phosphate solubilizing microorganisms by enrichment culture techniques, *Biochemistry and Molecular Biology Journal*, vol. 3, pp. 1.

Sharma, R., Sayyed, Z., Trivedi, M. H. and Gobi, T. A. (2013). Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils, *Springer Plus*, vol. 2, pp. 1-9.

Sileshi, G. W., Kihara, J., Tamene, L., Vanlauwe, B., Phiri, E. and Jama, B. (2022). Unravelling causes of poor crop response to applied N and P fertilizers on African soils. *Experimental Agriculture*. 58pp.

Szilas, C. (2002). The Tanzanian Minjingu Phosphate Rock. *Royal Veterinary and Agricultural*. Ph.D. Thesis for Award Degree at University Copenhagen, Copenhagen, Denmark.187pp.

Szilas, C., Semoka, J. M. R. and Borggaard, O. K. (2007). Establishment of an agronomic database for Minjingu phosphate rock and examples of its potential use. *Nutrient Cycling in Agroecosystems* 78(3): 225-237.

United Nations (2018). The sustainable development goals report 2018. 40pp.

Vikram, A. and Hamzehzarghani, K. (2008).Effect of phosphate solubilizing bacteria on nodulation and growth parameters of greengram (*Vigna radiata* L. Wilczek), *Research Journal of Microbiology*, vol. 3, pp. 62–72.

Vollset, S. E., Goren, E., Yuan, C. W., Cao, J., Smith, A. E., Hsiao, T., Bisignano, C., Azhar, G. S., Castro, E., Chalek, J., Dolgert, A. J., Frank, T., Fukutaki, K., Hay, S. I., Lozano, R., Mokdad, A. H., Nandakumar, V., Pierce, M., Pletcher, M., Robalik, T., Steuben, K. M., Wunrow, H. Y., Zlavog, B. S. and Murray, C. J. L. (2020). Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. *The Lancet* 396(10258): 1285–1306.

Wafula, W. N., Korir, N. K., Ojulong, H. F., Siambi, M. and Gweyi-Onyango, J. P. (2018). Protein, calcium, zinc, and iron contents of finger millet grain response to varietal differences and phosphorus application in Kenya. *Agronomy* 8(2): 1-24.

Warren, G. P., Robinson, J. S. and Someus, E. (2009). Dissolution of phosphorus from animal bone char in 12 soils. *Nutrient Cycling in Agroecosystems* 84(2): 167-178.

Weih, M., Westerbergh, A. and Lundquist, P. O. (2017). Role of nutrient efficient plants for improving crop yields: bridging plantecology, physiology, and molecular biology. In: Hossain, M. A., Kamiya, T., Burritt, D. J., Tran, L. S. P., Fujiwara, T. (eds)*Plant Macronutrient Use Efficiency: Molecular and Genomic Perspectives in Crop Plants*. Academic Press Ltd Elsevier Science Ltd, London. pp 31–44.

Widdig, M., Schleuss, P. M., Weig, A. R., Guhr, A., Biederman, L. A., Borer, E. T. and Spohn, M. (2019). Nitrogen and phosphorus additions alter the abundance of phosphorus-solubilizing bacteria and phosphatase activity in grassland soils. *Frontiers in Environmental Science* 7: 1-15.

Wu, L., Cui, Z., Chen, X., Yue, S.; Sun, Y., Zhao, R., Deng, Y., Zhang, W. and Chen, K.(2015) Change in phosphorus requirement with increasing grain yield for Chinese maize production. *Field Crops* 180: 216–220.

Yousefi, A. A., Khavazi, K., Moezi, A. A., Rejali, F. and Nadian, H. A. (2011). Phosphate solubilizing bacteria and arbuscular mycorrhizal fungi impacts on inorganic phosphorus fractions and wheat growth. *World Applied Science Journal* 15(9): 1310-1318.

Zaworotko, M. J., Clarke, H., Kapildev, A., Kavuru, P., Shytle, R. D., Pujari, T. and Ong, T. T. (2019). *Nutraceutical Co-Crystal Compositions.*University of South Florida (USF) Patents, 1017. 97pp.

CHAPTER FOUR

4.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

This study was conducted in selected fields of Kongwa District in Dodoma region to assess soil fertility status and effectiveness of phosphorus solubilizing bacteria (PSB) on enhancing phosphorus (P) availability to a maize (*Zea mays* L.) crop following application with Minjingu rock phosphate (MPR) in soils whose reaction ranges from slightly acid to neutral. Twenty-four (24) fields were selected and their fertility status was evaluated and only seven among the selected fields were chosen for trials establishment.

Fields were selected based on soil pH and assessed for their soil fertility status. After assessment of soil fertility status, trials in the chosen seven fields were established during the 2020/2021 cropping season in a randomized complete block design (RCBD) with maize as a test crop. PSB and Minjingu rock phosphate (MRP) wereco- applied where MPR was a basal fertilizer. Maize plants were harvested at maturity and total biomass weight was determined (converted into biological yield), grain weight determined (converted into grain yield), straw was analyzed for P concentration, and computations performed for straw P uptake, and P use efficiency.

Results from this study indicated that levels of N, P, K, S, Ca, Mg and Zn were low, however, there were large variations in nutrient deficiencies in different fields.Soil pH of study area ranged from extremely acid (3.73) to slightly alkaline (8.1). About 25% of all the soils had strong to moderate acid pH (≤5.5) while 75% had slightly acid pH (≥6≤8).
In the trial fields, main effect of fields' characteristics indicated that performance of maize and its analyzed parameters were statistically significant ($P< 0.001$) across the fields

reflecting heterogeneity in nutrient levels. The main effect of treatments indicated insignificant in all maize parameters analyzed. Results also did not show significant (*P* =0.427) interaction effects of field characteristics and treatment combination on the measured variables in maize.

The findings of the present study, apart from setting site specific fertilizer recommendations, also suggest that the performance of maize in the study area is dependent on the soil nutrient status especially for native P, N, and K.

I therefore recommend;

i. The results of the study area show deficient levels of N, P, K, S, Ca, Mg and Zn. However, there were large variations in nutrient deficiencies in different fields. This led into grouping of soils into twelve soil fertility groups. Therefore, application of fertilizers should be made on the basis of each soil fertility group identified in the study, for example, group 1 needs N containing fertilizers soil fertility, group 2 needs N and K while soil fertility group 3 needs N, P, K and Zn.Concurrently, since OC was generally low in the study area, increased use of organic fertilizers such as Farm Yard Manure, Compost and incorporation of crop residues and green manure is recommended to increase nutrient and moisture holding capacity, soil particle aggregation, improve soil tilth and organic carbon of the soils. Use of liming materials such as $CaCO_3$, $MgCO_3$, CaO, Ca $(OH)_2$ and Mg (OH) for those fields with strongly acid soils.

ii. It has been observed from this study that maize productivity has not been optimized with application of MPR and inoculation with solubilizing bacteria because of bad weather. Since the study was for one agricultural season, we recommend for further research by repeating in more than one season for better performance of the combination in slightly acid to neutral soils.

APPENDICES

Appendix 1: Geographical location of selected farmer's fields in Kongwa District for production of maize in Central Tanzania

Village	Farmer Name	Farm No.	Coordinates	
NGHUMBI	Timoth Elias Kusenha	1	S 06.31474	E 036.82544
			S 06.31471	E 036.82599
			S 06.31522	E 036.82577
	Lot Philemon malekela	2	S 06.31453	E 036.82654
			S 06.31479	E 036.82663
			S 06.31462	E 036.82679
	Dalali Lemnje	3	S 06.31402	E 036.84024
			S 06.31328	E 036.84130
			S 06.31356	E 036.84089
	Mary Charles Masala	4	S 06.30920	E 036.82176
			S 06.30899	E 036.82105
			S 06.30927	E 036.82114
	Luka Ndugai	5	S 06.30830	E 036.81967
			S 06.30793	E 036.81925
			S 06.30788	E 036.81953
	Meshaki Elias Kusena	6	S 06.32154	E 036.82645
			S 06.32184	E 036.82581
			S 06.32111	E 036.82637
IDUO	Robert Mgonda	1	S 06.26646	E 036.64792
			S 06.26670	E 036.64786
			S 06.26657	E 036.64772
			S 06.26641	E 036.64760
	Peter Msanya Mhingwa	2	S 06.26728	E 036.64790
			S 06.26751	E 036.64851
			S 06.26648	E 036.64849
	Mathias Ngiga	3	S 06.25990	E 036.65495
			S 06.25952	E 036.65509
			S 06.26006	E 036.65545
	Martin Mhina Katapira	4	S 06.27988	E 03664945
			S 06.28038	E 036.64929
			S 06.28000	E 036.64915
	John Magaya	5	S 06.27808	E 036.66543
			S 06.27819	E 036.66566
			S 06.27869	E 036.66521
	EmmanueL Makagu Mbaruka	6	S 06.27089	E 036.66504
			S 06.27097	E 03666558
			S 06.27049	E 036.66523
MLALI	Yona William	1	S 06.27791	E 036.74819
			S 06.27791	E 036.74773
			S 06.27738	E 036.74807
	Rehema Kaulule	2	S 06.27113	E 036.74724
			S 06.27124	E 03674675
			S 06.27200	E 036.74747
	Gambo Hussein	3	S 06.25989	E 036.74331
			S 06.26020	E 036.74250
			S 06.26055	E 036.74349
	Anderson Makuye	4	S 06.23935	E 036.74416
			S 06.23897	E 036.74410
			S 06.23943	E 036.74320
	Stanley Mkopi	5	S 06.26331	E 036.74689
			S 06.26292	E 036.74688

			S 06.26317	E 036.74673
			S 06.26479	E 036.74707
			S 06.26339	E 036.74692
		6	S 06.26488	E 036.74688
IHANDA			S 06.23055	E 036.71242
	Janeth Mangole		S 06.23049	E 036.71288
		1	S 06.23023	E 036.71261
	Anjelina Sijiha Kisalula		S 06.21949	E 036.71648
			S 06.21947	E 036.71527
		2	S 06.21920	E 036.71504
	Kezia Ndahane		S 06.22898	E 036.68988
			S 06.22832	E 036.69020
			S 06.22783	E 036.68949
			S 06.22830	E 036.68934
		3	S 06.22830	E 036.68959
	Doricia Mjema		S 06.26127	E 036.69366
			S 06.26134	E 036.69397
		4	S 06.26191	E 036.69350
	Leah Maranda		S 06.222642	E 036.71109
			S 06.22588	E 036.71114
		5	S 06.22616	E 036.71082
	Thelufena Kusalula		S 06.22865	E 036.71164
			S 06.22871	E 036.71111
		6	S 06.22841	E 036.71133