

**IMPACT OF TILEMSI PHOSPHATE ROCK ON SOIL PHOSPHORUS
AVAILABILITY AND CROP YIELD IN THE SAHELIAN ZONE OF MALI**

KNUST



BY

ALIOU BADARA KOUYATE OCTOBER, 2015

i

**IMPACT OF TILEMSI PHOSPHATE ROCK ON SOIL PHOSPHORUS
AVAILABILITY AND CROP YIELD IN THE SAHELIAN ZONE OF MALI**

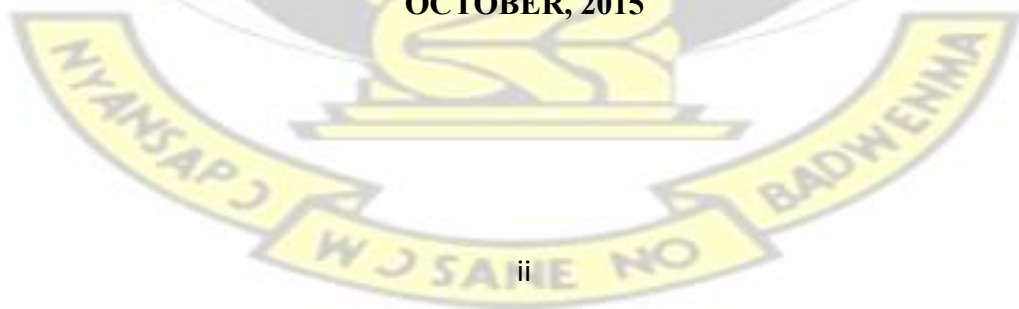
A Thesis submitted to the Department of Crop and Soil Sciences, Faculty of Agriculture, College of Agriculture and Natural Resources, Kwame Nkrumah University of Science and Technology, Kumassi, Ghana, in partial fulfillment of the requirements for the award of the degree of

KNUST

DOCTOR OF PHILOSOPHY IN SOIL SCIENCE

BY Aliou Badara KOUYATE Agronomy Engineer (2000) MSc. in Environmental Protection (2007)

OCTOBER, 2015



.....

.....

.....

Signature

• • • • •



.....

Signature

• • • • •

.....

Signature

• • • • •

.....

Signature

.....

.....

Signature

• • • • •

DEDICATION

This thesis is dedicated to Dr Mamadou D Doumbia IER / CRRA of Sotuba

KNUST



ACKNOWLEDGEMENTS

I wish to thank the Almighty ALLAH for giving me good health, strength and perseverance needed to complete this thesis.

This study was funded by the Alliance for Green Revolution in Africa. The work presented in this thesis would not have been possible without the support and assistance of many people and institutions. I am deeply grateful to AGRA for the four year scholarship given to me.

I express my profound gratitude to my supervisors Rev Prof Mensah Bonsuh and Dr. Vincent Logah of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi Ghana and Dr. Francis M. Tetteh of Soil Research Institute (SRI) Kwadaso whose patience, understanding and constructive criticisms made the completion of this work possible.

I would like to express my gratitude to the Coordinators of AGRA Soil Science PhD programme in KNUST; Profs. R C Abaidoo , E. Y. Safo and C. Quansah for their mentorship and guidance.

To my external supervisor, Dr. Mamadou D. Doumbia of IER who fell sick at the commencement of the research work. I would like to say “meilleur santé”

I am also greatly indebted to Dr. Hamidou Konare, Dr. Mama Kone, for their scientific guidance and valuable comments and suggestions throughout this study. I shared unforgettable moments and a warm social life with the other AGRA Soil Science PhD students. I particularly want to thank Djeneba, Bejame Gonda, Ali Bachir, Mary, Bismark, Abdul Aziz and Onawumi.

I appreciate Baba, Bakaye, and all the field laborers for their support during the field work.

My appreciation also goes to the staff of the Soil Laboratory, IER (Institut d'économie rural) for providing technical support and enabling environment for the laboratory analysis. I thank also the staff and personnel of OPIB (Office du perimeter irrigue de Baguineda) to accept to release me for this study.

I express my gratitude to my family, especially my father Mahamdou Lamine, mother, Kadiatou Sacko and brothers, Bamoussa, Abdramane, Sory and Coumba for their support throughout my school life.

I greatly thank my lovely wife, Seynabou Dembele and my daughter Fatoumata Goundo for their support and patience during the time I was away either at Konobougou, Sotuba or in Ghana.

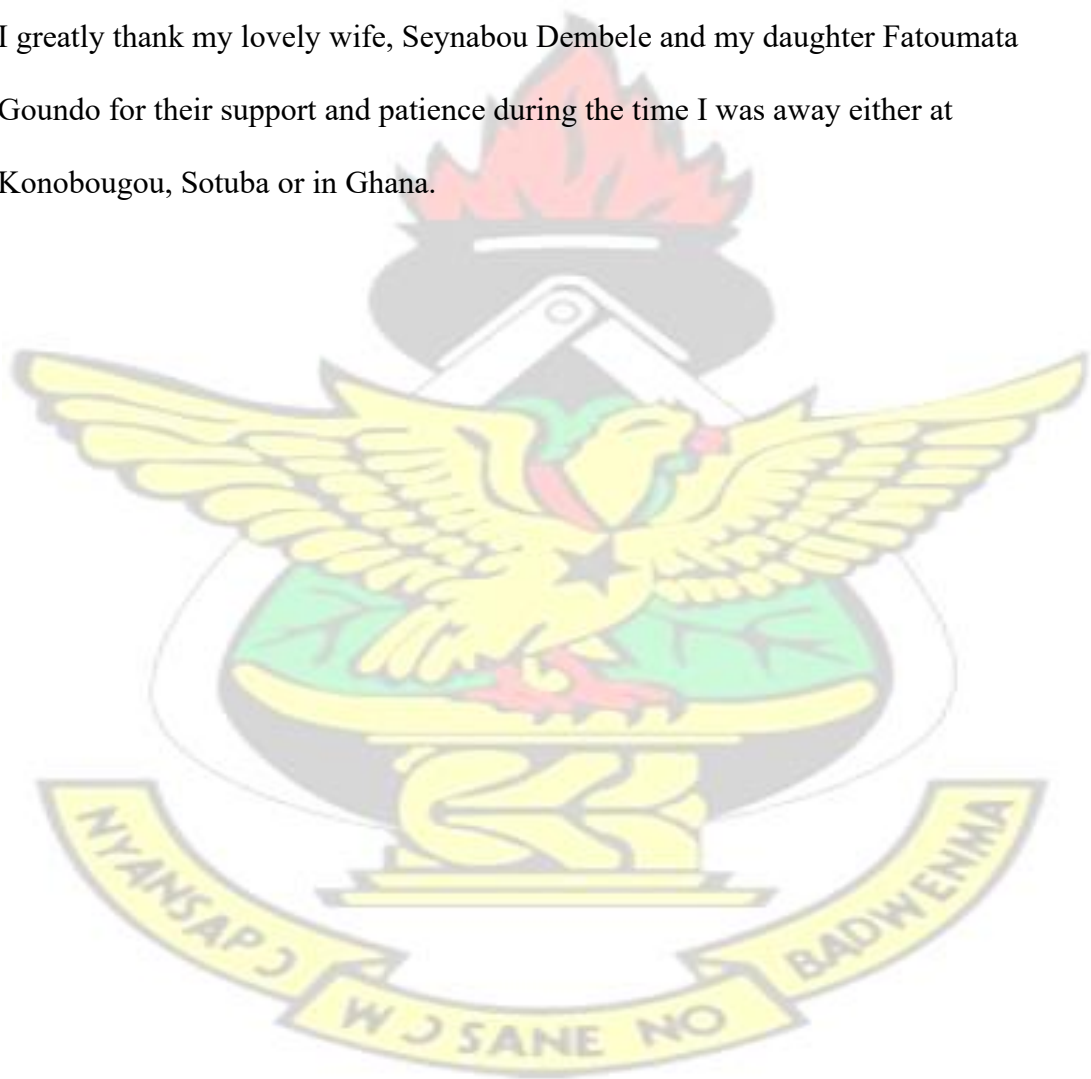


TABLE OF CONTENTS

	PAGE
DECLARATION	I
DEDICATION	II
ACKNOWLEDGEMENTS	III
TABLE OF CONTENTS	V
LIST OF TABLES XII LIST OF FIGURES XV	
ABSTRACT XVIII	
CHAPTER ONE	1
1.0 INTRODUCTION	1
CHAPTER TWO	4
2.0 LITERATURE REVIEW	4
2.1 Soil phosphorus forms	4
2.1.1 Inorganic phosphorus	4
2.1.2 Organic phosphorus	5
2.2 The role of phosphorous in crop growth	5
2.3 Phosphorous retention in soils	6
2.3.1 Adsorption reaction	6
2.3.2 Precipitations reactions	8
2.4 Phosphorus requirement for crop growth	9
2.4.1 Phosphorus sorption isotherm	9
2.4.2 Standard phosphorus requirement	10
2.5 Phosphorus use by crops	11
2.5.1 . Phosphorus uptake by crops	11
2.5.2 Phosphorus use efficiency by crops	12
2.6. Phosphate rock	13
2.6.1 Types of phosphate rock	13
2.6.2 Reactivity and solubility of phosphate rocks	14

2.6.2.1 Chemical extractant test	14
2.6.2.2. Rock phosphate properties affecting its dissolution	15
2.6.2.3. Soil properties affecting rock phosphate dissolution	16
2.6.2.4. Influence of plant species on rock phosphate dissolution	18
2.6.2.5. Climatic conditions	18
2.6.3. Solubility of phosphate from PR through amendments	19
2.6.4. Effect of rock phosphate on crop growth and yield	21
2.6.5 Effect of rock phosphate application on soil chemical properties	22
2.7. Tilemsi phosphate rock (TPR)	23
2.7.1. Location of TPR deposits in Mali	23
2.7.2. Characteristics of TPR	24
2.8 Tillage practices	25
2.8.1 Types of tillage practices	25
2.8.2 Impact of contour ridge on crop growth, yield and soil properties	26
2.8.3 Effect of contour ridge practice on soil water availability	26
CHAPTER THREE	27
3.0 MATERIALS AND METHODS	27
3.1 Description of the study site	27
3.2 Study 1: Laboratory evaluation of standard phosphorus requirement (SPR) for major soils of Mali	29
3.2.1 Evaluation of standard phosphorus requirement	30
3.2.2 Evaluation of sorption data	31
3.2.3 Data analysis	32
3.3 Study 2: Field assessment of the efficiency of Tilemsi rock phosphate compared to DAP at different rates of application under different tillage practices	32
3.3.1 Soils of the study site	32
3.3.2 Experimental design	33
3.3.3 Land preparation	34
3.3.4 Fertilizer application	34
3.3.5 Planting material	34
3.3.6 Plant culture	35
3.3.7 Weed control	35
3.3.8 Soil sampling and laboratory analysis	35
3.3.8.1 Determination of soil pH	35

3.3.8.2	Determination of organic carbon	36
3.3.8.3	Determination of total nitrogen	36
3.3.8.4	Determination of available P	37
3.3.8.5	Determination of exchangeable basic cations	38
3.3.8.6	Determination of exchangeable acidity	39
3.3.8.7	Determination of particle size distribution	40
3.3.9	Analysis of plant materials	41
3.3.9.1	Determination of phosphorus and nitrogen	41
3.3.10	Harvesting	43
3.3.11	Parameters measured	43
3.3.12	Estimation of nutrient uptake	44
3.3.13	Assessment of gravimetric soil water content	44
3.3.14	Economic analysis	45
3.4	Study 3: Field assessment of the response of high yielding sorghum variety to different forms of Tilemsi rock phosphate	45
3.4.1	Soil of the study site	46
3.4.2	Experimental design	46
3.4.3	Phosphate rock	46
3.4.4	Planting material	46
3.4.5	Plant culture	47
3.4.6	Weed control	47
3.4.7	Fertilizer application	47
3.4.8	Soil sampling and laboratory analysis	47
3.4.9	Harvesting	47
3.4.10	Parameters measured	47
3.4.11	Crop growth rate	48
3.4.12	Plant height	48
3.4.13	Phosphorus partial balance	48
3.4.14	Plant sample analysis	48
3.4.15	Data analysis	49
	CHAPTER FOUR	49
	4.0 RESULTS	49
	4.1 Study 1: Laboratory evaluation of standard phosphorus requirement for major soils of Mali	49

4.1.1 Phosphate sorption isotherm	49
4.1.2. Relationship between P sorption characteristics and soil properties	50
4.2 Study 2: Assessment of the efficiency of Tilemsi rock phosphate compared to DAP at different rates of application under different tillage practices	53
4.2.1: Effects of tillage practices and soil amendments on soil chemical properties	53
4.2.1.1: Soil pH	53
4.2.1.2: Soil organic carbon	57
4.2.1.3 Soil total N	58
4.2.1.4 : Soil available P	58
4.2.1.5 Exchangeable Ca	63
4.2.1.6 Exchangeable Mg	64
4.2.1.7 Exchangeable K	64
4.2.1.8 Exchangeable acidity	65
4.2.1.9 Effective cation exchange capacity	65
4.2.2 Effect of soil tillage practices on gravimetric soil water content at 0-10 and 10-20 cm depths	67
4.2.3 Correlation between available phosphorus and some selected soil properties after harvest	68
4.2.4 Effects of tillage practices and soil amendments on maize growth and yield	71
4.2.4.1 Maize grain yield	71
4.2.4.2 Effects of tillage practices and soil amendments on maize biomass yield	74
4.2.5 Correlation between maize yield and some selected soil properties	75
4.2.6 Effects of tillage practices and soil amendments on N and P uptake by maize grain and biomass	77
4.2.6.1 Phosphorus uptake by maize grain	77
4.2.6.2 Phosphorus uptake in maize biomass	81
4.2.6.3 Effects of soil tillage practices and soil amendments on nitrogen uptake in maize grain	83
4.2.6.4 Nitrogen uptake in maize biomass	85
4.2.7 Effects of tillage practices and soil amendments on phosphorus use efficiency	87
4.2.7.1 Relative agronomic effectiveness as affected by tillage practices	87

4.2.7.2	Effects of tillage practices and soil amendments on phosphorus agronomic efficiency (PAE), partial factor productivity (PFP) and recovery efficiency (PRE)	88 89
4.2.7.3	Value cost ratio	94
4.3	Study 3: Assessment of the response of sorghum to different forms of Tilemsi rock phosphate	95
4.3.1	Effect of soil amendments on sorghum yield and growth	95
4.3.1.1	Sorghum grain yield	95
4.3.1.2	Sorghum biomass yield	96
4.3.2	Effect of soil amendments on soil chemical properties	99
4.3.2.1	Soil pH	99
4.3.2.2	Soil organic carbon and total nitrogen	100
4.3.2.3	Soil available phosphorus	100
4.3.2.4	Effect of soil amendments on soil exchangeable cations and ECEC	103
4.3.3	Effect of soil amendments on phosphorus uptake by sorghum	111
4.3.3.1	Grain phosphorus uptake	111
4.3.3.2	Effect of soil amendments on P uptake by sorghum biomass	113
4.3.4	Effect of soil amendments on nitrogen uptake	115
4.3.4.1	Effect of soil amendments on nitrogen uptake by grain	115
4.3.4.2	Effect of soil amendments on nitrogen uptake by sorghum biomass	116
4.3.5	Correlation between sorghum grain yield, biomass yield, and some soil properties after harvesting	119 119
4.3.6	Relationship between available P, crop growth parameters and some soil properties	120 120
4.3.7	Effect of soil amendments on phosphorus use efficiency indices	122
4.3.8	Effect of soil amendments on phosphorus partial balance	125
4.3.9	Effect of soil amendments on value cost ratio	126
CHAPTER FIVE		127
5.0 DISCUSSION		127
5.1	Study1: Evaluation of standard phosphorus requirement for major soils of Mali	127
5.2	Study2: Assessment of the efficiency of Tilemsi rock phosphate compared to DAP at different rates of application under different tillage practices	130
5.2.1	Effect of soil amendments on selected soil chemical properties	130

5.2.1.1	Soil pH	130
5.2.1.2	Organic carbon	131
5.2.1.3	Total N	131
5.2.1.4	Available phosphorus	132
5.2.1.5	Exchangeable cations	134
5.2.1.6	Effective cation exchange capacity	135
5.2.2	Relationship between some soil properties and available phosphorus at harvest	136
5.2.3	Effects of tillage practices and soil amendments on maize grain and biomass yields	138
5.2.4	Relationship between maize yield and some selected soil properties	139
5.2.5	Effects of tillage practices and soil amendemnts on nutrient (N and P) uptake in miaze	140
5.2.6	Effects of tillage practices and soil amendments on phosphorus use efficiencies by maize	141
5.2.7	Effects of tillage practices and soil amendments on value cost ratio (maize)	143
5.3	Study 3: Assessment of the effects of different forms of Tilemsi phosphate rock on sorghum growth and yield and soil chemical properties	144
5.3.1	Effects of soil amendments on sorghum grain and biomass yields	144
5.3.2	Effect of soil amendments on selected soil chemical properties	146
5.3.2.1	Soil pH	146
5.3.2.2	Total nitrogen	146
5.3.2.3	Available phosphorus	147
5.3.2.4	Exchangeable cations	148
5.3.2.5	Effective cation exchange capacity	149
5.3.3	Effect of soil amendments on nutrient uptake (phosphorus and nitrogen)	149
5.3.4	Relationship between available P crop growth parameters and some soil properties	150
5.3.5	Phosphorus use efficiency	151
5.3.6	Effect of soil amendments on soil phosphorus partial balance	151
5.3.7	Value cost ratio	152
CHAPTER SIX		153
6.0 SUMMARY, CONCLUSION AND RECOMMENDATIONS		153

6.1 Summary and conclusion	153
6.2 RECOMMENDATIONS	155
REFERENCES	156
APPENDICES	177

LIST OF TABLES

	PAGE
Table 2. 1 Solubility of PRs in conventional reagents	15
Table 2.2a Chemical composition of TPR	25
Table 2.2 b Composition of Tilemsi phosphate rock	25
Table 3.1 Characteristics of the soils under study	31
Table: 3.2 Chemical properties and texture of the soils used for maize and sorghum cultivation	34
Table: 3.3 Forms of Tilemsi phosphate rock used from Toguna Agro Industry	48
Table 4.1 Standard phosphorus requirement and amounts of TPR required for the soils under study	51
Table 4.2 Phosphorus sorption characteristics of the different soils	52
Table 4.3 Correlation coefficients describing relationships between P sorption characteristics and selected soil properties	53
Table 4.4 Effects of soil amendments and tillage practices on soil pH, SOC, total N and available P in 2013	56
Table: 4.5 Effects of soil amendments and tillage practices on soil pH, SOC, total N and available P in 2014	57
Table 4.6 Effects of soil amendments and tillage practices on soil exchangeable bases, exchangeable acidity and soil ECEC in 2013	67
Table 4.7 Effects of soil amendments and tillage practices on soil exchangeable bases, exchangeable acidity and ECEC in 2014	68
Table 4.8 Effect of tillage practices on gravimetric soil water content in 2013	69
Table 4.9 Effect of tillage practices on gravimetric soil water content in	

	2014	69
Table: 4.10	Relationship between soil available P and some soil properties at harvest.	70
Table 4.11	Multiple regression of soil available P with soil properties at harvest in 2013	71
Table 4.12	Multiple regression of soil available P with soil properties at harvest in 2014	71
Table 4.13	Effects of soil amendments and tillage practices on maize grain and biomass yields	75
Table 4.14	Relationship between some selected soil properties and maize grain yield at harvest	76
Table 4.15	Multiple regression of grain yield with soil properties in 2013	77
Table 4.16	Multiple regression of grain yield with soil properties in 2014	78
Table : 4.17	Effects of tillage practices and soil amendments on phosphorus uptake by maize grain and biomass	83
Table 4.18	Effects of tillage practices and soil amendments on nitrogen uptake by the grain and biomass	87
Table 4.19	Maize grain yield and relative agronomic effectiveness of TPR and DAP on CR plot	89
Table 4.20	Maize grain yield and relative agronomic effectiveness of TRP compared to DAP on HT plot	89
Table 4.21	Effects of tillage practices and soil amendments on PFP, PAE and PRE in 2013 and 2014	91
Table 4.22	VCR of soil amendments and tillage practices for maize cultivation in 2013 and 2014	95
Table 4.23	Effect of soil amendments on sorghum grain and biomass yields	98
Table 4.24	Effect of soil amendments on soil pH, soil organic carbon, total nitrogen and available P in 2013	103
Table 4.25	Effect of soil amendments on soil pH, soil organic carbon, total nitrogen and available P in 2014	103

Table 4.26	Effect of soil amendments on soil exchangeable cations and ECEC in 2013	109
Table 4.27	Effect of soil amendments on soil exchangeable cations and ECEC in 2014	110
Table 4.28	Effect of soil amendments on P uptake by sorghum grain and biomass	113
Table 4.29	Effect of soil amendments on N uptake by sorghum grain and biomass	117
Table 4.30	Relationship between sorghum grain and biomass yields, and some selected soil properties at harvest in 2013 and 2014	118
Table 4.31	Multiple regression of grain yield with some selected soil properties in 2013	118
Table 4.32	Multiple regression of grain yield and some selected soil properties in 2014	119
Table 4.33	Correlation between available P, some soil properties and sorghum growth factors	120
Table 4.34	Multiple regression analysis between available P, sorghum growth factors and some soil properties in 2013	120
Table: 4.35	Multiple regression analysis between available P, sorghum growth factors and some soil properties in 2014	121
Table 4.36	Effect of soil amendments on partial factor productivity, phosphorus agronomic efficiency and phosphorus recovery efficiency in 2013	122
Table 4.37	Effect of soil amendments on partial factor productivity, phosphorus agronomic efficiency and phosphorus recovery efficiency in 2014	123
Table : 4.38	Phosphate partial balance	124
Table 4.39	Effect of soil amendments on value cost ratio (sorghum)	125

KNUST

LIST OF FIGURES

	PAGE
Figure: 2.1 Mechanism of P adsorption on Al oxide surface	7
Figure 2.2 General geological setting of the phosphate deposit in Eastern Mali	24
Figure 3.1 Location of the study site (Konobougou)	29
Figure 4.2 Interaction effects of phosphorus type and application rate on soil pH in 2014	58
Figure 4.1 Interaction effects of phosphorus type and application rate on soil pH in 2013	58
Figure 4.3 Interaction effects of phosphorus type and application rate on soil available phosphorus in 2013	61
Figure 4.4 Interaction effects of phosphorus type and application rate on soil available phosphorus in 2014	62
Figure 4.5 Interaction effects of tillage practices and phosphorus type on soil available phosphorus in 2013	62
Figure 4.6 Interaction effects of tillage practices and phosphorus type on soil available phosphorus in 2014	63
Figure 4.7 Interaction effects of tillage practices and phosphorus rate of application on soil available phosphorus in 2013	63
Figure 4.8 Interaction effects of tillage practices and phosphorus rate of application on soil available phosphorus in 2014	64
Figure 4.9 Interaction effects of phosphorus type and rate of application	

	on maize grain yield in 2013	73
Figure 4.10	Interaction effects of phosphorus type and rate of application on maize grain yield in 2014	73
Figure 4.11	Interaction effects of tillage practices and phosphorus type on maize biomass yield in 2014	75
Figure 4.12	Interaction effects of tillage practices and phosphorus type on P uptake by maize grain in 2013	80
Figure 4.13	Interaction effects of tillage practices and phosphorus rate of application on P uptake by maize grain in 2013	80
Figure 4.14	Interaction effects of tillage practices and phosphorus type on P uptake by maize grain in 2014	81
Figure 4.15	Interaction effects of tillage practices and phosphorus rate of application on maize grain P uptake in 2014	81
Figure 4.16	Interaction effects of tillage practices and phosphorus type on P uptake by maize biomass in 2014	83
Figure 4.17	Interaction effects of phosphorus type and rate of application on nitrogen uptake by maize grain in 2013	85
Figure 4.18	Interaction effects of phosphorus type and rate of application on nitrogen uptake by maize grain in 2014	85
Figure 4.19	Interaction effects of tillage practices and phosphorus type on N uptake by maize biomass in 2013	87
Figure 4.20	Interaction of tillage practices and soil amendments on phosphorus agronomic efficiency in maize in 2013	92
Figure 4.21	Interaction of tillage practices and soil amendments on P partial factor productivity in maize in 2013	92
Figure 4.22	Interaction of tillage practices and soil amendments on phosphorus recovery efficiency in maize in 2013	93
Figure 4.23	Interaction of tillages practice and soil amendements on phosphorus agronomic efficiency in maize in 2014	93
Figure 4.24	Interaction of tillage practices and soil amendements on P partial factor productivity in maize in 2014	94

Figure 4.25	Interaction of tillage practices and soil amendments on phosphorus recovery efficiency in maize in 2014	94
Figure 4.26	Interaction effects of phosphorus type and rate of application on sorghum grain yield in 2013	98
Figure 4.27:	Interaction effects of phosphorus type and rate of application on sorghum grain yield in 2014	99
Figure 4.28:	Interaction effects of phosphorus type and rate of application on sorghum biomass yield in 2013	99
Figure 4.29:	Interaction effects of phosphorus type and rate of application on biomass yield in 2014	100
Figure 4.30	Interaction effects of phosphorus type and rate of application on soil exchangeable calcium in 2013	105
Figure 4.31	Interaction effects of phosphorus type and rate of application on soil exchangeable magnesium in 2013	106
Figure 4.32	Interaction effects of phosphorus type and phosphorus rate of application on soil exchangeable K in 2013	107
Figure 4.33	Interaction effects of phosphorus type and rate of application on soil exchangeable acidity in 2014	108
Figure 4.34	Interaction effects of phosphorus type and rate of application on soil ECEC in 2013	109
Figure 4.35	Interaction effects of phosphorus type and rate of application on grain P uptake by sorghum grain in 2013	111
Figure 4.36	Interaction effects of phosphorus type and rate of application on P uptake by sorghum grain in 2014	111
Figure 4.37	Interaction effects of phosphorus type and rate of application on P uptake by sorghum biomass in 2013	112
Figure 4.38	Interaction effects of phosphorus type and rate of application on P uptake by sorghum biomass in 2014	113
Figure 4.39	Interaction effects of phosphorus type and rate of application on N uptake by sorghum grain in 2013	114
Figure 4.40	Interaction effects of phosphorus type and rate of application on N uptake by sorghum grain in 2014	115

Figure 4.41	Interaction effects of phosphorus type and rate of application on N uptake by sorghum biomass in 2013	116
Figure 4.42	Interaction effect of phosphorus type and rate of application on N uptake by sorghum biomass in 2014	116

KNUST



ABSTRACT

Low soil phosphorus availability is a major constraint to crop production in Mali. The usual fertilizer shortage and the high cost of water soluble phosphate make it a less accessible option for resource poor farmers. This study explored the use of locally available Tilemsi phosphate rock (TPR) to optimize soil P availability for sustainable crop yield. A laboratory study was first carried out to define the standard phosphorus requirement (SPR) using phosphorus sorption isotherm method. The standard phosphorus requirements of four representative soils of Mali were evaluated and phosphorus adsorption data fitted to the Langmuir equation. The amounts of phosphorus required to give 0.20 mg L^{-1} varied with soil ranging from 7.10 to 24 mg kg^{-1} (i.e. 16 to $54 \text{ kg of P ha}^{-1}$) whilst sorption maxima ranged from 59 to 200 mg kg^{-1} . The study indicated that soil texture (particularly clay content) is a prominent factor influencing standard phosphorus requirement. The values of standard phosphorus requirement were higher compared to the recommended dose of Tilemsi phosphate rock used for all the soils under study. A field experiment was then carried out to assess the effects of Tilemsi phosphate rock powder and pellet forms, and DAP application at different rates under two tillage practices on the growth and yield of maize as well as soil properties and phosphorus use efficiency indices. The experiment consisted of three rates of phosphorus: 0 kg ha^{-1} (control), 11 kg ha^{-1} (recommended rate of TPR application), and 16 kg ha^{-1} (SPR of the study soil), three types of phosphorus: TPR (powder), TPR (pellet) and DAP and two tillage practices: contour ridge and hoe tillage. The contour ridge (CR) out yielded the hoe tillage (HT) with a percentage grain yield increment of 22% and 16% , respectively in 2013 and 2014. Comparing CR and HT, maize biomass yield was increased by 32% and 14% and phosphorus uptake by 44% and 65% , respectively in 2013 and 2014 under contour ridge tillage

compared to hoe tillage. Application of TPR and DAP significantly increased grain yield in the decreasing order DAP > Powder > Pellet > Control plot in both seasons of study. Increasing in P application rate from 11 to 16 kg ha⁻¹ increased crop yield by 26 % and 20 %, respectively in 2013 and 2014. Application of TPR and DAP significantly ($P < 0.05$) influenced soil available phosphorus and pH in both seasons. Soil available phosphorus was not significantly correlated ($P > 0.05$) with soil moisture in both seasons. The increase in soil available phosphorus (from TPR) under contour ridge seemed more linked to high uptake of phosphorus from soil solution. The relative agronomic effectiveness (RAE) was higher under CR than HT. The powder form of TPR produced significantly higher value ($P < 0.05$) compared to the pellet form with respect to phosphorus use efficiency indices evaluated in the study. A second field experiment was conducted to evaluate the effects of different forms of Tilemsi phosphate rock: TPR+ (NH₄)₂SO₄, TPR + KCl, TPR + (NH₄)₂SO₄ + KCL and sole application of TPR as pellet on agronomic characteristics of sorghum and soil properties. The experiment consisted of three rates of phosphorus application (P0, P11, and P16) and four amended types of TPR factorially arranged in randomized complete block design (RCBD) with three replications. Combined application of TPR with sulphate of ammonia significantly ($P < 0.001$) increased grain yield in both seasons relative to the control. The impact of the soil amendments on grain yield followed the decreasing order: P+SAM > P+K+SAM > P+K > Pellet > Control in 2013. A similar trend was observed in 2014 except that pellet TPR produced higher grain yield than TPR + KCl. Increase in P application from 11 to 16 kg ha⁻¹ increased the grain yield with percentage increment of 36 % and 21 %, respectively, in 2013 and 2014. The application of phosphate rock significantly influenced soil available phosphorus, exchangeable Ca, K and effective cation exchange capacity in both seasons. The

combined application of TPR with sulphate of ammonia increased the dissolution of TPR and release of phosphorus due to high uptake of P rather than its acidifying effect.

KNUST



CHAPTER ONE

1.0 INTRODUCTION

Mali, like any other sub-Saharan country, is confronted by massive problems related to food security because of decreasing per-capita food production. Extreme poverty (per capita incomes of less than one U.S. dollar per day), poor soil fertility and nutrient depletion continue to represent huge obstacles to securing the needed harvests from crops (Roland *et al.*, 1997).

However, soil fertility in Africa has seldom been considered as critical issue by the developed communities, which until recently have focused primarily on other biophysical constraints such as soil erosion, droughts, and the need for improved crop germplasm (Crosson and Anderson, 1995; De Vries and Toennissen, 2001). While the use of fertilizers is indispensable to alleviate nutrient constraints, average nutrient consumption in Sub Saharan Africa (SSA) is only 8.3 kg ha⁻¹ (Sanginga and Woomer, 2009).

Phosphorus (P) deficiency in soil is widely considered the main biophysical constraint to food production in large areas of farmlands in sub- humid and semi- arid Africa (Bationo *et al.*, 1996). To raise soil productivity in the region, application of P is an absolute necessity, and thus external inputs other than P may not even be cost-effective as long as the P status is not raised to satisfactory levels (Sedogo *et al.*, 1991). Unlike nitrogen (N) which can be supplied indirectly through biological fixation by rhizobia in symbiosis with legumes, P must be added to the depleted soils in a concentrated form either as P-containing fertilizers or locally available phosphate rocks (Straaten, 2002).

The use of reactive phosphate rocks has often been suggested as one of the technologies for alleviating phosphorus deficiency in tropical agricultural systems (Sale and Mokwunye, 1993). Throughout the tropics, direct applications of highly reactive phosphate rocks (PR) have often shown to be an agronomical comparable substitute for water-soluble phosphate (WSP) fertilizers (Chien and Menon, 1995).

Although the use of TPR in crop production in Mali has received research attention, most of it was related to grinding, mixing PR with organic materials and partial acidulation of PR. Until now there is scanty information on the appropriate soil management option that can improve the overall agronomic effectiveness of TPR under low and erratic rainfall pattern. The use of TPR as P fertilizer in Mali has been suggested on crops with blanket recommended rate (Henao and Baanante, 1999). It is important to determine the optimum rate at which TPR can be used for major soils of Mali, with respect to their capacity and intensity factor and study the adsorption characteristics of those soils on phosphorus availability from TPR.

Many of the phosphate rock resources in the world are inherently low in their reactivity and are not likely to release sufficient P into the soil solution to be agronomically effective. The most effective way to make PR more reactive can be achieved by the breakdown of apatite through partial acidulation, for example with sulphuric or phosphoric acid (Straaten, 2002). But these improvements are still beyond the reach of poor countries. Toguna Agro Industry in Mali has developed a new blend of TPR with $(\text{NH}_4)_2 \text{SO}_4$ and KCl to enhance its solubility. However, no study has been done to evaluate the impact of these formulations on soil chemical properties and agronomic characteristics of crops on acidic soils in the Sahel area of Mali.

This study therefore aimed generally at evaluating the availability of phosphorus from TPR and its effectiveness to sustain improved maize and sorghum growth and yield in Sahel area of Mali. The specific objectives were to:

- i. determine the P sorption characteristics and standard phosphorus requirement (SPR) for four main soils of Mali; ii. assess the effectiveness of different forms and rates of Tilemsi phosphate rock compared to water soluble phosphate (DAP) on maize grain yield and soil properties under different tillage practices;
- iii. evaluate the efficiency of new blend Tilemsi phosphate rock cogranulation with KCl and $(\text{NH}_4)_2\text{SO}_4$ to support growth and yield of high yielding sorghum variety in Sahelian area of Mali; iv. appraise the comparative cost effectiveness of TPR and DAP, and also TPR blend and sole application of TPR under different soil management options.

The above specific objectives were formulated to test the following hypotheses:

- (i) Soil management option such as contour ridge can improve phosphorus availability from TPR and increase maize grain yield
- (ii) Combining KCl, $(\text{NH}_4)_2\text{SO}_4$ with Tilemsi phosphate rock will enhance soil phosphorus availability under field conditions in Sahel area of Mali.
- (iii) Phosphorus sorption isotherm can predict the amount of Tilemsi phosphate rock needed to meet crop requirement on major soils of Mali.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil phosphorus forms

Phosphorus is involved in many of the reactions that keep plants and animals alive, and is thus essential for all living organisms. The total P content in soil is commonly between 100 and 3000 mg of P kg⁻¹ soil (Tiessen and Moir, 1993) depending on the P content of the parent material and subsequent amelioration. Phosphorous is found in two different forms in soil: inorganic and organic. The conversion of plant available inorganic phosphates into unavailable organic forms is termed immobilization. The reverse is termed mineralization. Both processes can occur concurrently in the soil (Cornforth, 2012).

2.1.1 Inorganic phosphorus

Inorganic forms of soil P consist of apatite, complexes of iron and aluminum phosphates, and P adsorbed on clay particles. Apatite, a P- containing rock, is present in less weathered soils in various forms representing the primary P forms: fluoroapatite ($\text{Ca}_{10}\text{F}_2(\text{PO}_4)_6$), hydroxyapatite ($\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$) and oxyapatite ($\text{Ca}_{10}\text{O}(\text{PO}_4)_6$) (Lindsay *et al.*, 1989). The native P content in soils depends on the nature of the parent material and the degree of weathering. During soil development, apatite P is weathered and gradually transformed to other inorganic and organic P forms through precipitation to secondary minerals or through plant or microbial uptake. Secondary P minerals formed in acidic soils are mainly Al and Fe phosphates such as variscite, $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$, and strengite, $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ (Smeck, 1985). In neutral to alkaline soils, different types of secondary Ca-phosphates predominate: dicalcium or octacalcium phosphates, hydroxyapatite and eventually less soluble apatite (Lindsay *et al.*, 1989). The main

inorganic forms of phosphorus in soil are H_2PO_4 and HPO_4^{2-} . These are the forms in which phosphorus is used by plants.

2.1.2 Organic phosphorus

Organic phosphorus (Po) in soil can be associated either with soil organic matter (humus) or recently added organic debris of plant or animal origin. Before this Po can be recycled and used by plants it has to be broken down by soil microbes through mineralization to release inorganic phosphate ions (Johnston, 2000). This process is highly influenced by soil moisture, temperature, physical, chemical properties, and soil pH and redox potential (Eh) (Shen *et al.*, 2011). Po generally accounts for 30% to 65% of the total P in soils (Harrison, 1987). Organic P sources, such as crop residues and animal manure, generally have low P content. These organic P sources must be supplied in massive amounts to provide adequate P rates, rendering their application economically unfeasible in many locations and conditions (Shen *et al.*, 2011).

2.2 The role of phosphorous in crop growth

Phosphorus, along with nitrogen and potassium, is a nutrient that plants need in relatively large quantities for normal growth. Phosphorus plays a vital role in energy storage and transformation for plant metabolic process (Brady and Weil, 1996). In the plant metabolic process, many P-containing compounds are synthesized. Phosphorus also has a structural role in nucleic acids, ATP, enzymes and phospholipids, which have basic roles in essential physiological processes including photosynthesis, respiration, cell division and cell enlargement (Raghothama, 1999). Moreover, phosphorus stimulates early growth, root formation and the ability of plants to absorb water and other nutrients and stimulates flower blooms (Marschner, 1995; Schachtman *et al.*, 1998).

Phosphorus deficient plants are stunted, with limited root systems and thin stems. Symptoms include reduced tillering in cereals and in corn, seedlings look stunted and older leaves may be purple because of high levels of anthocyanin (purple pigments). Fruit trees deficient in P have fewer and shorter shoots and malformed fruits and seeds. Thus, not only are yields poor but crop quality is poor where P is deficient (Uchida, 2000)

2.3 Phosphorous retention in soils

Phosphorus in the soil is only partly soluble and not very mobile. Generally, plants can only utilize a small fraction of the total P in soil, corresponding with the so-called available-P. This amount is related to the so-called labile soil P, sometimes referred to as intensity of the nutrient in the profile (Batjes, 2011). The author reported that phosphate retention is an inherent property of a soil and it does not change. It is a continuous (time dependent) process that occurs in all soils that gradually renders phosphate ions temporarily unavailable to plants. Phosphate sorption occurs by both specific adsorption and precipitation reactions, but the adsorption is considered to be the most important process controlling P availability in soils over a short period (Batjes, 2011).

2.3.1 Adsorption reaction

Specific adsorption occurs through ligand exchange (Figure 2.1) when P anions replace the hydroxyl groups on the surface of Al and Fe oxides and hydrous oxides

(Haynes and Mokolobate, 2001).

P is not chemically stable in the water-soluble form in the presence of soil.

Watersoluble P in soil solution readily reacts, largely with aluminum and iron, to form less soluble and more stable compounds. The reactions mostly take place on the surfaces of soil constituents (clays; oxides of iron and aluminum; organic matter; and

aluminum and iron compounds coating surfaces of sands). After the initial surface reaction, the adsorbed P diffuses slowly towards the interior of the particle and so becomes less available to plants (Bollan and Duraismy, 2003). The whole reaction, adsorption plus penetration, is called sorption. Penetration of adsorbed P into the soil particles continues even in dry soil, albeit more slowly (Arai and Sparks, 2007).

Phosphorus in soil solution reacts with soil minerals and its sorption and desorption process are influenced by soil aggregate size. Clayey materials with more than 20% iron or aluminum oxides in their clay- size particles sorb large quantities of added phosphorus, transforming them into slowly soluble iron and aluminium phosphates (Figure 2.1) that are not immediately available to plants (Sanchez *et al.*, 2003). High phosphorus retention is related to high clay content, therefore most sandy red soils do not fall in this category (Sanchez *et al.*, 2003). Alternatively, most fine to medium textured soils have large capacities to hold phosphate by adsorption and precipitation.

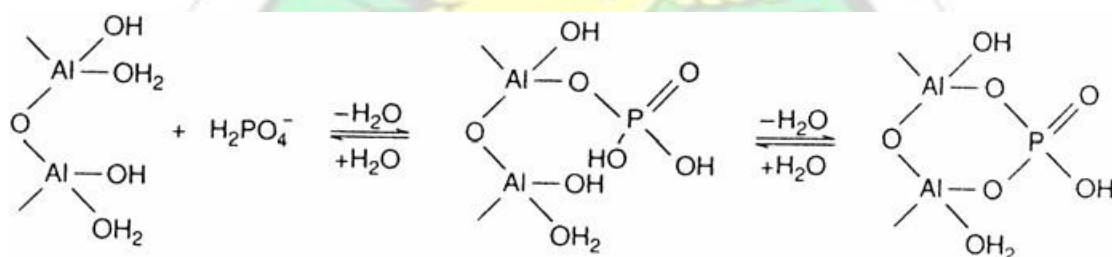


Figure: 2.1. Mechanism of P adsorption on Al oxide surface (Haynes and Mokolobate, 2001)

Decomposition of Organic Matter (OM) produces hydrogen which is responsible for acidity. Organic supplements have been reported to increase P availability in P-fixing soils (Agbenin and Igbokwe, 2006) and humic substances enhance the bioavailability of P fertilizers in acidic soils (Hua *et al.*, 2008).

The addition of OM to soils may increase phosphorus availability by decomposition and mineralization of organic-P, or by abiotic processes such as ligand-exchange effects on phosphate adsorption. However, the OM content of highly weathered soils has been shown to be negatively correlated with phosphate adsorption capacity. For example, Singh and Gilkes (1991) found a negative correlation between phosphate sorption by soil and soil OM (SOM) content for 97 highly weathered soils of Western Australia. The importance of organic matter is ambiguous because it can act in two ways, either by sorbing P or by blocking sorption sites of inorganic particles (Stuanes, 1982).

2.3.2 Precipitations reactions

Under some conditions, soluble P may also react with ions in the soil solution. This is a precipitation reaction. Precipitation reactions occur when insoluble P compounds form and precipitate. Availability of phosphorus is primarily dependent upon the pH of the soil. However, soil pH as such does not affect phosphorus retention directly. Rather, it is a proxy that shows how certain minerals (i.e., iron, aluminum and calcium), interact with phosphorus in the soil, and it is this interaction that affects phosphorus availability and/ or retention (Batjes, 2011).

At low pH (<5.5), soils have greater amounts of iron and aluminum in solution, which can form very strong bonds with phosphate ions. Under such low conditions, variscite and strengite are likely regulating factors of inorganic P solubility (Pierzynski *et al.*, 2005).

In neutral-to-calcareous soils, P retention is dominated by precipitation reactions (Lindsay *et al.*, 1989), although P can also be adsorbed on the surface of Ca carbonate and clay minerals (Devau *et al.*, 2010). Phosphate can precipitate with Ca, generating

dicalcium phosphate (DCP) that is available to plants. Ultimately, DCP can be transformed into more stable forms such as octocalcium phosphate and hydroxyapatite (HAP), which are less available to plants at alkaline pH (Arai and Sparks, 2007).

2.4 Phosphorus requirement for crop growth

Plant and soil analysis are used extensively to diagnose the P status of farming systems. Adequate P nutrition at the seedling stage is important for plant development. Insufficiency of P at this stage cannot be remedied by side-dressed P because of the lack of mobility of P in soils (Hedley and Bolan, 1997). Therefore, pre-plant soil tests offer a better method of predicting P requirements for establishing crops.

2.4.1 Phosphorus sorption isotherm

Several P extraction methods using acids, organic and inorganic complexing agents, or alkaline solutions have been developed. The extractants often extract all or part of the labile P, which is considered available to plants during their growth cycle, plus an undefined proportion of other forms of soil P. Because several soil properties influence the extraction of P, it is not surprising that there is no one best extractant at all conditions (Fox, 1992).

Adsorption isotherms describe the adsorption of solution ions by solids at constant temperature in quantitative terms. An adsorption isotherm shows the amount of solute adsorbed by an adsorbent as a function of the equilibrium concentration of the adsorbate (Tan, 1998). The quantity of P disappearing from soil solution is considered sorbed (Papini *et al.*, 2000; Hue and Fox, 2010). The quantity of P required to attain a specific P concentration in an equilibrated soil solution is a useful parameter obtained from the phosphorus isotherm (Uwumarongie-IIori *et al.*, 2012).

This approach has an advantage over conventional method of soil testing in that it integrates P intensity, capacity and quantity aspect of the soil, all of which play important role in controlling the P flux to most of the growing plants. Moreover, fertilizer requirement can be estimated directly from P sorption curves. Therefore, matching P fertilizer types with soil physical and chemical properties may be an efficient strategy for rational use of chemical fertilizer P (Shen *et al.*, 2011).

2.4.2 Standard phosphorus requirement

Phosphorus sorption relationships are commonly used in the determination of standard phosphorus requirement (SPR) of crops. According to Fox (1981), SPR is the concentration of P in solution that is non-limiting to plant growth. For most crops, the amount of P in soil solution with 0.2 mg P L⁻¹ (P 0.2) has been shown to be the threshold over which no response to P is observed (Iyamuremye *et al.*, 1996; Gichangi *et al.*, 2008). The P requirements, estimated in this manner aim at building up the status of soil phosphorus by a single application to a level which, thereafter, only requires maintenance application to replenish losses owing to plant uptake, removal by erosion or continuing slow reactions between phosphate and soil (Henry and Smith, 2003).

Most crops require from 0.2 to 0.5 % P in tissue dry matter for normal growth, and P deficiency is likely when the P content drops below 0.1 % (Jones *et al.*, 1991; Hue *et al.*, 2000).

Large areas of Africa, particularly in the semiarid tropics, are dominated by sandy soils with low P sorption and hence low fertilizer P requirements (Warren, 1992). A modest annual application of 15 to 20 kg P ha⁻¹ is usually adequate for these soils (Bationo and Mkwunye, 1991). Previous application of P reduces a soil's capacity to adsorb further P. Doumbia (1990), Hue and Fox (2010) suggested that a portion of the previously added phosphate had been converted into a form which was occupying P adsorption

sites, blocking them from further reaction. Hue and Fox (2010) reported that with past P fertilization the uncultivated Halii soil sorbs 1.5 times more P than the cultivated.

2.5 Phosphorus use by crops

2.5.1. Phosphorus uptake by crops

Nutrient uptake is the process by which plant roots take up nutrients present in soil solution, with such nutrients subsequently distributed to aerial portions of the plant (Havlin *et al.*, 2005). Nutrient uptake is affected mainly by environmental conditions, management practices, the concentration of nutrients and the form in which nutrients are present in the soil (Allen and David, 2007). Phosphorus application significantly increases P uptake. Akande (2011) showed that P uptake by maize was significantly increased as the rate of application increased. P uptake was increased by 53, 48, and 73% in *Ilora*, *Ibadan* and *Epe* soils respectively at the highest rate of 60 kg ha⁻¹.

Growth conditions such as soil and climatic factors as well as biotic factors have influence on crop P uptake. Wasonga *et al.* (2008) observed that sites with unfavorable soil condition of high Al saturation resulted in relatively low P uptake. Low uptake of P can also be attributed to lower biomass production as the P uptake is a product of biomass and P content (Onwonga *et al.*, 2013). Furihata *et al.*, 1992 reported that P deficiency observed in acid soils is often associated with high P fixation and P uptake rates are highest between pH 5.0 and 6.0 where H₂PO₄⁻ dominates. Teng and Timmer (1994) found that P uptake is strongly correlated with grain yield and total dry matter yield. According to the authors, combined use of N and P fertilizers contribute to increase P uptake than the sole P application. This increase of P uptake could be attributed to the synergistic N enhancement of P uptake. Yang and Jacobsen (1990) proposed that the

decreased efficiency in P uptake following P application was a result of conversion of fertilizer P to relatively insoluble forms.

2.5.2 Phosphorus use efficiency by crops

Nutrient use efficiency is the ability of a plant to utilize soil available nutrients to result in measurable yield or yield parameters such as plant height, leaf development, dry matter and fruit / grain production (Hati *et al.*, 2006).

The agronomic effectiveness of P depends on the soil conditions (Zapata and Roy, 2004). Generally, in acid soils with pH below 5.0, the efficiency of PR is as high as that of acidulated phosphate (Mengel, 1986). Thuita *et al* (2005) reported that the acidic soils of Siaya, in Western Kenya with pH of 4.76 (H₂O) was ideal for favourable solubilization of PRs. Juma (unpublished data) reported that Minjugu phosphate rock (MPR) had about 70 to 75 % relative agronomic effectiveness (RAE) on acid soils in Western Kenya. Also, higher rainfall contributes to high RAE. Musa *et al* (2012) reported low dissolution of Sokoto rock phosphate under low rainfall conditions.

The increasing rate of phosphorus application was found to decrease PUE and RAE (Huissen, 2009). According to the author, the utilization of nutrient decreased as increasing the rate of nutrient application as stated by the law of limiting factors and Liebig's law of the minimum. The fertilizer efficiency improved significantly, when integrated (organic and inorganic) source of P was used (Yamoah *et al.*, 2002). Zapata and Roy (2004) found that P agronomic use efficiency for Minjingu Rock Phosphate varied from 21 kg grain per kg P applied to 43 kg grain per kg P applied in diammonium phosphate plots.

2.6. Phosphate rock

2.6.1 Types of phosphate rock

Phosphate rock is a globally accepted but imprecise term describing any naturally occurring geological material that contains one or more phosphate minerals suitable for commercial use. The term comprises both the unprocessed phosphate ore as well as the concentrated phosphate products (Notholt and Highley, 1986). The phosphate raw materials of interest to agronomists and fertilizer industry are a complex assemblage of minerals grouped under the generic heading of phosphate rock (PR).

Thus, the term “phosphate rock” is a trade name (Mokwunye *et al.*, 1996).

There are two main types of phosphate rock deposits - sedimentary and igneous. Sedimentary phosphate and igneous rocks that have been subjected to extremely deep burial (high pressure and perhaps shearing forces and/or heat) may be further categorized as a third type of phosphate rocks, metamorphic phosphate rock (IFDC, 2010). The principal mineral in igneous and metamorphic PR is fluorapatite $\{Ca_{10}(PO_4)_6F_2\}$. On the other hand, carbonate apatite or francolite is the most common constituent of sedimentary PR. Most commercial phosphate rocks and most of the deposits in West Africa belong to the sedimentary group. Sedimentary PR is also the most important source for direct application (Straten, 2002). The world phosphate resources are distributed, according to their type, approximately as follows: 75% from sedimentary marine deposits, 15–20% from igneous, metamorphic and weathered deposits, and 2–3% from biogenic sources (bird and bat guano accumulations) (Zaher and Abouzeid, 2007).

2.6.2. Reactivity and solubility of phosphate rocks

Reactivity of rock phosphate can be defined as the rate at which P in the apatite is released under favorable chemical conditions. Phosphate rocks of igneous and metamorphic origin are less reactive because of their crystalline form. The sedimentary rock deposits which possess microcrystalline structure are highly reactive (Kaleeswari and Subramanian, 2001). Phosphate rock reactivity and solubility can be evaluated using different methods, the following being the most common:

2.6.2.1. Chemical extractant test

There are various methods for evaluating phosphate rocks for direct application (Chien, 1993). One of these approaches is solubility test using chemical extractant. Solubility test using chemical extractant offer a simple and rapid method for classifying and then selecting PRs according to their potential effectiveness (Table 2.1). The most common solutions are neutral ammonium citrate (NAC), citric acid (CA) and formic acid (FA) (Gholizadeh *et al.*, 2009).

Table 2. 1: Solubility of PRs in conventional reagents

Reagents	Tilemsi	Kodjari	Taiba	Anecho
	-----(% of total P)-----			
NAC	13.5	8.0	5.4	4.8
Citric Acid (2%)	38.4	24.5	21.3	21.3
Formic Acid (2%)	61.2	48.4	41.5	40.9
Isotopic dilution	3.78	0.17	0.12	0.28

Source : Truong *et al.* (1978)

Hedley and Bolan (1997) stated that PRs with > 30 % total P soluble in 2% citric acid are reactive and suitable for direct application. Bollan and Gilkes (1997) stated that PR

containing more than 65 to 70 % of its total P soluble in 2 % formic acid is reactive. Solubility measurement cannot be used to predict specific yield response but they can serve as a useful means of predicting relative performance of one source to another and thus, assisting in selection of the most appropriate source (Ghosal and Chakraborty, 2012).

2.6.2.2. Rock phosphate properties affecting its dissolution

As PRs are relatively insoluble minerals, their geometric surface area is an important parameter determining their rate of dissolution. The finer the particle size, the greater the geometric surface area and degree of contact between the soil and PR particles and, thus, the greater the PR dissolution rate (FAO, 2004).

Generally the solubility of PR, increases with smaller particle size. Chien and Friesen (1992) showed that the solubility of unground reactive PR (35 mesh: 0.5 mm) was less than that of the same but ground PR (100 mesh: 0.15mm), but their agronomic effectiveness was similar under field and greenhouse conditions. However, fine grinding a low-reactivity phosphate rock will not significantly increase P availability due to its insoluble mineralogical structure (Nathan and Mikelsen, 2008). Bolland and Gilkes (1989) reported that finely powdered North Carolina Phosphate Rock (NCPR) was about 5 - 32 % as effective as freshly-applied superphosphate in the year of application, and finely powdered NCPR, was at best, 1.5 to 2 times as effective as granular NCPR.

When small rates of rock phosphate are applied, the particles are farther apart and so discrete phosphate rock particles react with soil. In such a case each phosphate rock particle will dissolve to its maximum extent in soil (Bolland, 2007). The effectiveness of PRs varied widely with the P-application rate and the duration of the experiment.

Increasing the rate of PR application decreases its dissolution and hence its agronomic effectiveness. When applied to soils, large amounts of protons are needed to make these PRs effective. This also means that the amounts of PR applied must be balanced in relation to the amounts of available protons, as high rates will work to the disadvantage of the effectiveness of the PR itself (Mowo, 2000). Low soil solution P concentrations due to high rates of PR have been reported by Rajan *et al.* (1991). High rates of PR are not desirable as they will introduce more CaCO_3 hence reducing the amounts of proton that would otherwise be available for dissolving P from calcium phosphate in the PR (Mowo, 2000).

2.6.2.3. Soil properties affecting rock phosphate dissolution

When rock phosphate is applied to the soil, the water insoluble phosphorus in the fertilizer must be converted to water soluble phosphorus before it can be used by plants. The soil properties that favor the dissolution of PR are low pH (less than 5.5), low solution concentration of Ca ions, low P fertility levels and high organic-matter content (FAO, 2004).

Phosphate rock dissolution involves the consumption of protons (H^+ ions), and the release of Ca and phosphate ions to soil solution. Consequently, soils with a large source of free protons (acid soils), and large sinks for Ca and phosphate ions (that is, low exchangeable Ca and high P-retention capacity) are well suited for PR application and dissolution (Mowo, 2000). Acid soils are potential soils for utilization of rock phosphates as fertilizer for direct use. As a simple guideline, the use of PRs, depending on their reactivity, is generally recommended in soils with a pH of 5.5 or less. The dissolution of PR diminishes with increasing pH up to 5.5 but the decline is more rapid above this pH level (Bollan *et al.*, 1990). The release of P from PR generally increases

with a greater P- fixing capacity of the soil (FAO, 2004). Adsorption and precipitation of soluble P provide a sink that favors PR dissolution (Chien *et al.*, 2010).

However, as the soil P-fixing capacity increases, the concentration of soluble P released from PR may initially decrease more rapidly than that from water soluble phosphate (WSP) sources, despite the fact that the dissolution of PR increases with an increase of soil P-fixing capacity (Chien *et al.*, 2010). Although increasing the P_{sink} of the soil increases the rate of PR dissolution, there is strong evidence that the plant availability of dissolved P is reduced (Kanabo and Gilkes, 1987). Mokuwunye and Hammond (1992) reported that PR dissolution may be increased by a high P sorption capacity of the soil, however its effectiveness is lower in such soils. Hammond *et al* (1986) ascribed this poor performance of PRs in soil with high P sorption capacity to poor root development during the early stages of crop growth due to P deficiency.

Aaroon *et al* (2013) reported that the fixation trend depends on the amount of available P and the amount of P added. When available P is high, less P is fixed and vice versa. Since dissolution of PR also releases Ca, soils with high initial Ca content typically have slower PR dissolution, in accordance with mass action law. Calcium carbonate is more soluble than the most chemically reactive apatite and its dissolution increases the concentration of Ca^{2+} and pH at the surface of apatite (Bollan and Duraisamy, 2003). Thus, it is not surprising that accessory CaCO_3 reduces the rate of rock phosphate dissolution in some soils. However, under field conditions where Ca may be removed by plant uptake and/or due to leaching, this effect may be minimized.

The positive influence of soil organic matter on increasing the agronomic effectiveness of PR has been reported (Chien, 2003), which is due to its high cation exchange capacity (CEC) and organic acids produced as a result of microbial and chemical transformation of organic debris. The decomposition products of organic matter have

chelation capacity which lowers the activity of polyvalent cations (Ca, Fe, Al) that form insoluble salts with P and thus liberate P from basic phosphates of these elements.

2.6.2.4. Influence of plant species on rock phosphate dissolution

The usefulness of PR as nutrient sources varies with crop species. Acidification in the plant rhizosphere accounts for some of the differences among crop species to utilize PR (Chien *et al.*, 2010).

Moreover, high root density facilitates the intensive exploration of a large soil volume for P because of the presence of a large number of fine roots per unit of soil volume. Crops that possess high Ca uptake capacity are more suited for PR use. In this respect, finger millet is most suited for PR use, followed by pearl millet and maize (Flach *et al.*, 1987).

2.6.2.5. Climatic conditions

Rainfall is the most important climatic factor that influences PR dissolution and its agronomic effectiveness. Increased soil water brought about by rainfall or irrigation increases PR dissolution (Weil *et al.*, 1994). The process is affected by speedy neutralization of the hydroxyl ions released and removal of Ca and other reaction products from the area adjacent to PR particles (FAO, 2004). Adequate water supply will encourage plant growth and P uptake by plants, leading to increased agronomic effectiveness of PRs (FAO, 2004). For direct application of PR, experience in Australia and New Zealand would indicate an annual rainfall requirement of at least 850 mm for PRs to be agronomically similar to water-soluble fertilizers (Hedley and Bollan, 1997). However, the rainfall requirement depends on soil properties.

Gillard *et al.* (1997) stated that for highly reactive PRs (formic soluble > 70 %) a total annual rainfall of 700 mm to 1000 mm (depending on soil type) is required for them

to be agronomically effective; for moderately reactive PRs 900 to 1200 mm was required. Moisture film surrounding the PR particles are required to provide the H^+ ions needed for the neutralization of the dissolution products. High rates of leaching in sandy West African soils would promote the rapid removal of PR dissolution products, thus creating favorable environments for PR dissolution (Hanafi *et al.*, 1992).

Highly significant interactions were observed between TPR response and the amount of rainfall after planting. Sites with basal applications of TPR in semiarid and subhumid areas, receiving at least 50 mm of rainfall during the first month after planting, produced about 30 % - 40 % higher yields of maize, cotton, and groundnut (Henao and Baanante, 1999). Average crop yield can be reduced by 20 % in sorghum, millet and groundnut cropping systems and about 40 % for maize in cotton – maize cropping system when annual rainfall is reduced from 900 to 500 mm in Sudanian zone of Mali (Henao and Baanante, 1999).

2.6.3. Solubility of phosphate from PR through amendments

A practice to enhance the agronomic effectiveness of low reactive PRs is blending PR with water-soluble phosphates, commonly TSP or acidifying fertilizers. According to Chien *et al.* (1987), small amounts of water-soluble phosphates act as a starter dose for the plants until P from the PR becomes available to the plants. This initial starter dose of water-soluble P will stimulate root development. The denser root system will then increasingly utilize the remaining PR (Chien *et al.* 1996). Mnkeni *et al.* (2000) showed that Panda PR was ineffective when applied alone but the mixture of Panda PR plus triple super phosphate (TSP) or its compacted product increased wheat, maize, and soybean yields and P uptake significantly.

The increased effectiveness of PRs in combination with water soluble phosphate (WSP) was shown by Chien *et al.* (1996) who reported that the effectiveness of PR in combination with TSP increased by 165 % for maize and 72 % for cowpea. The increased effectiveness of PR when applied as a dry mixture can be ascribed to the root-priming effect of soluble P and, therefore, increased root exploitation of the PR added (FAO, 2004).

The mixture of PRs with sulphate of ammonia enhances its P release. Sulphate of ammonia (SAM) apart from supplying the important N and S nutrients acidifies the soil, hence creating conducive environment for PR dissolution. Soil pH linearly decreased with the application of N by ammonium sulphate and urea fertilizers.

However, the magnitude of the pH decrease was greater for using ammonium sulphate than urea (Fageria *et al.*, 2010).

Further, the supply of important plant nutrients improves crop growth, creating a P concentration gradient through increased P demand. The consequence of this is increase in PR dissolution. The time of application of N fertilizer such as sulphate of ammonia play an important role in the dissolution of PRs. Mowo (2000) suggested that for improving the effectiveness of Minjugu phosphate rock (MPR), sulphate of ammonia should be applied in concomitant with MPR before planting. Jing *et al.* (2010) suggested that localized application of phosphates plus ammonium significantly enhances P uptake and crop growth through stimulating root proliferation and rhizosphere acidification in a calcareous soil. Ammonium N also improves uptake of residual phosphorus and micronutrients. Averaged across 19 sites high in phosphorus, ammonium sulphate performed as well or better than starter applications of 10-30-10 NPK (Roth, 2006) in corn.

2.6.4. Effect of rock phosphate on crop growth and yield

Direct application of phosphate rock to soil as a possible alternative to the more expensive soluble phosphate fertilizers in tropical cropping system has received considerable attention in recent years (Taalab and Badr, 2007).

Hong-Qing *et al.* (1996) reported in ultisol, yields from PR and TSP treatments were almost identical when the rate of phosphorus application was the same, when the same level of phosphorus fertilizer was applied, the residual effect of phosphate rock was better than that of triple superphosphate.

Shahandeh *et al.* (2004) found that application of Tilemsi phosphate rock (TPR) increased millet yield by up to 89 % compared to the control. The augmentation in millet yield was attributed to increase in the plant available P and Ca. Bollan *et al.* (1990) reported that incorporation of PR ensures a steady supply of P over a long period and also provides a high rooting density to crops. The positive effect of phosphate rock on soil properties with amendments and consequently on crop growth and grain yield has been reported by several authors. Okande *et al.* (2011) showed that application of Ogun rock phosphate (OPR) as a source of P, with or without amendments improved the growth and seed yield of kenaf. However, amending the OPR with various organic wastes and urea gave comparable growth and seed yields with NPK application (Okande *et al.*, 2011). According to the authors, they also give comparable relative agronomic effectiveness with NPK fertilization and, therefore, can be used as alternative.

High grade of PR mixed with sulphate of ammonia performed better than DAP at the same rate of P (60 kg ha⁻¹ of P) in pot experiment with *Phaseolus vulgaris* as test crop. The average biomass recorded after 25 days of sowing was 6.08 g and 3.86 g, respectively for PR and DAP (Raguram and Ramachandra, 2014).

2.6.5 Effect of rock phosphate application on soil chemical properties

Among the significant chemical and nutritional constraints on crop growth on acid soils are deficiencies of calcium (Ca) and magnesium (Mg) nutrients. As the apatite mineral in PR is Ca-P, there is a potential to provide Ca nutrient if there are favourable conditions for apatite dissolution. Furthermore, many sources of PR contain free carbonates, such as calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), that can also provide Ca and Mg in acid soils. However, if dissolution of free carbonates raises pH and exchangeable Ca around PR particles significantly, it can hinder apatite dissolution and thus reduce P availability of PR (Chien and Menon, 1995).

For example, Chien (1977) found that Huila PR (Colombia), which contained about 10 percent CaCO_3 , increased soil solution pH from 4.8 to 6.2 in one week compared with other PRs that increased pH to 5.1.

In a three-year field trial conducted in central China, Hu *et al.* (1997) reported that exchangeable Ca increased from 1194 mg kg^{-1} with the control to 1300–2100 mg kg^{-1} with PR treatments. The corresponding exchangeable Mg levels were 330 mg kg^{-1} with the control and 350 – 400 mg kg^{-1} with the PR treatments. Because the content of apatite-bound Mg is very small (unlike apatite-bound Ca), it is expected that PR will not increase soil exchangeable Mg significantly unless the PR contains a significant amount of dolomite (FAO, 2004)

The dissolution of apatite in PR releases anions (CO_3^{2-} and PO_4^{3-}) that can consume H^+ ions and, thus, it can increase soil pH, depending on PR reactivity (Hellums *et al.*, 1989). The same authors reported that, if a PR contains a significant amount of free carbonates, it can further increase soil pH. However, although an increase in soil pH may reduce the Al saturation level, it can also reduce apatite dissolution at the same

time. The optimum condition would call for a soil pH that is high enough to reduce the Al saturation level but still low enough for apatite dissolution to release P.

In a five-year field trial on an Oxisol fertilized with various PR sources, Chien *et al.* (1987) reported that the pH increased from 4.1 with the control to 4.7 – 5.0 with the PR treatments, the corresponding increase in exchangeable Ca was from 0.17 cmol₊ kg⁻¹ with the control to 0.31 – 0.56 cmol₊ kg⁻¹ with the PR treatments. However no significant effect on exchangeable Al was observed. In their study with the red soil of China, Hu *et al.* (1997) reported that the soil pH increased from 4.8 with the control to 4.9–5.3 with the PR treatments. However, Shahanadeh *et al.*, (2004) found that TPR had no significant effect on soil pH despite the huge amount applied but reduced Al toxicity and increased Ca content (from 0.22 to 2.87 cmol₊ kg⁻¹) and soil available P. The precipitation of soluble Al to Al-P compounds by the release P are partly responsible for reduction in soil aluminium content after addition of PR (Shahandeh *et al.*, 2004).

2.7. Tilemsi phosphate rock (TPR)

2.7.1. Location of TPR deposits in Mali

Deposits of rock phosphate in Mali are known since 1930. The PR deposits are found in the north eastern part of Mali, in the Tilemsi valley (Figure 2.2). At present, a number of deposits are known and grouped under the name of Bourem including the Tamaguilelt, Chanomaguel, Tin-hina, Sagariguita (Samit) deposits. The best-studied area of phosphate rocks in the Tilemsi area is that of Tamaguilelt (17° 40' N; 0° 15' E). Here, the unconsolidated phosphate sediments consist mainly of fish and reptile bone debris as well as coprolites (Straaten, 2002). Approximately, 10 million tons at the Tamaguilelt deposit are located beneath 15 m of overburden (Sustrac, 1986).

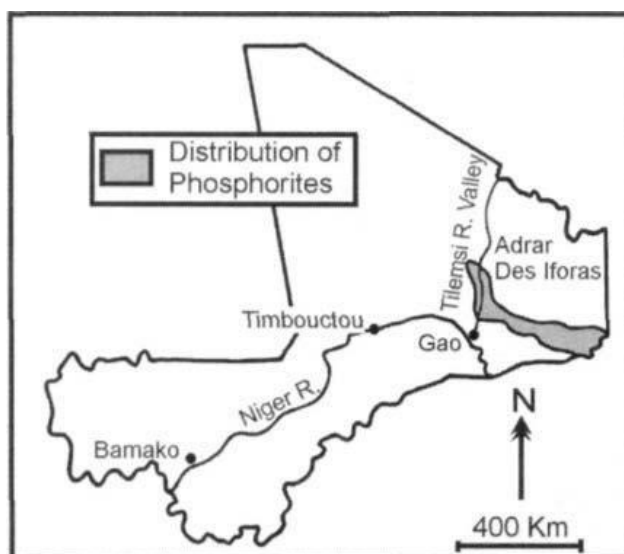


Figure 2.2: General geological setting of the phosphate deposit in Eastern Mali (Pascal and Traore 1989).

The reserve was estimated to be 20 million tons with an average P_2O_5 content of 27–28 percent. Tilemsi phosphate rock (TPR) is a medium reactive rock suitable for direct application. TPR has solubility greater than 40% in 2% formic acid (Truong *et al.*, 1978). This reactivity is attributable to a relatively high degree of carbonate substitution for phosphate in the rock minerals. The entire production of TPR is used within the country.

2.7.2. Characteristics of TPR

The mineralogical composition of mineral varies from site to site. In-depth studies have indicated that the main components of the TPR are phosphorus (25-32 %) and calcium (35 – 45 %) (Table 2.2a and 2.2b)

Table 2.2a: Chemical composition of TPR

Chemical composition	% in weight
CaO	39.20
P_2O_5	27.60
F	2.50
CO_2	2.00
MgO	0.44

Na ₂ O	0.32
K ₂ O	0.13
Fe ₂ O ₃	7.10
Al ₂ O ₃	2.70
SiO ₂	13.90
Total S	0.30

Source : Henao and Baanante (1999)

Table 2.2 b: Composition of Tilemsi phosphate rock

<u>Item</u>	<u>Composition</u>	<u>Weight (%)</u>
Apatite (Francolite)	Ca _{9.64} Na _{0.12} Mg _{0.05} (PO ₄) _{6.51} F _{2.10} (CO ₃) _{0.49}	77
Quartz	SiO ₂	8
Montmorillonite	Ca _{0.24} Na _{0.01} Mg _{0.36} Fe _{0.02} Al _{1.25} Si _{3.07} O ₁₀ (OH) ₂ H ₂ O	7
Goethite	FeO(OH)	8

Source : Henao and Baanante (1999)

Detailed mineralogical investigations have identified the phosphate mineral as francolite with crystallographic unit-cell “a” value of 9.331 Å indicating a relatively highly reactive PR. Indeed, the neutral ammonium citrate solubility of Tilemsi PR is high (42% P₂O₅) (Debrah, 2000; Somado *et al.*, 2003) making it suitable for direct application as phosphate fertilizer.

2.8 Tillage practices

According to Blanco-Canqui and Lal (2008), tillage is a major component of soil management. It refers to the mechanical operations performed for seedbed preparation and optimum plant growth.

2.8.1 Types of tillage practices

The no-till system is a specialized type of conservation tillage consisting of a onepass planting and fertilizer operation in which the soil and the surface residues are minimally disturbed (Parr *et al.*, 1990). The surface residues of such a system are of

critical importance for soil and water conservation. Hoes and spades in different shapes and weights are the tools used for hand-tillage operation, unless contract ploughing with animals or tractors is used. Tillage depth and intensity with hand tools is very limited, but as it also leaves the soil exposed it will equally lead to soil degradation and erosion (FAO, 2014).

Contour ridges sometimes called contour furrows or micro watersheds, are used for crop production. Ridges follow the contour at a spacing of usually 1 to 2 meters. Runoff is collected from the uncultivated strip between ridges and stored in a furrow just above the ridges. Crops are planted on both sides of the furrow (Doumbia *et al.*, 2008).

2.8.2 Impact of contour ridge on crop growth, yield and soil properties

Contour ridge is a potential technique of soil management option which can be easily adopted by poor resource farmers in Mali. The use of this tillage practice on different crop has given satisfactory result with different crops. In this respect, Doumbia *et al.* (2008) reported that contour ridge increased maize yield by 38% , sorghum by 39 % and cotton yields by 7% in Mali, peanut and sorghum yields by 25% in Senegal, and maize yield in Gambia from 9 to 30%. This improvement of grain yield under contour ridge technique is due to its moisture retention capacity which enhances crop growth and nutrient uptake by crop.

2.8.3 Effect of contour ridge practice on soil water availability

The principal objective of the CR technology is to retain or capture rainfall on the field, which helps to overcome the typically low infiltration rate of the soils (Kablan *et al.*, 2008). This retention of water reduces destructive runoff and enables multiple uses of the captured rainfall. As a result of the increased infiltration of rainfall, water

availability increases, improving crop growth and reducing erosive runoff as shown in long-term studies initiated by Gigou *et al.*(2006). Contour ridge reduced runoff of seasonal rainfall by 26%, increased soil moisture in crop root zone by 16% and available moisture for deep rooted plants by 64 % and ground water recharge by 29 % on the other hand contour ridge increased deep drainage and ground water recharge and increased soil organic concentration by 14% after three years in Senegal (Doumbia *et al.*,2008).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the study site

This study was undertaken to enhance soil phosphorus availability following Tilemsi rock phosphate application. Three studies comprising one laboratory and two field experiments were conducted. The laboratory experiment was conducted at the research station of the institut d'economie rural (IER) in Sotuba-Bamako in 2013 cropping season. The field experiments were carried out at Konobougou during the 2013 and 2014 cropping seasons.

Sotuba is located on latitude 13°10'2N and longitude 5°55'8W of the Greenwich meridian while Konobougou is located at 12° 55'N 6°46'W in the Sahelian zone of Mali (Figure 3.1). The field experimental site (Konobougou) is characterized by lateritic uplands alternating with gentle slopes and lowlands, in which rainfall ranges from 600 to 800 mm (Kablan *et al.*, 2008) whilst the length of growing season ranges from 90 to 100 days. The area is characterized by a high amplitude maximum temperature of 42 °C and a minima of 24 °C in December - January and an average of

32 ° C in May. The area experiences alternating two main seasons: the dry season and the rainy season (CSA, 2007).

The topography of the region is dominated by flat surfaces with an average altitude of about 300 m and hills that seldom exceed 400 m in altitude.

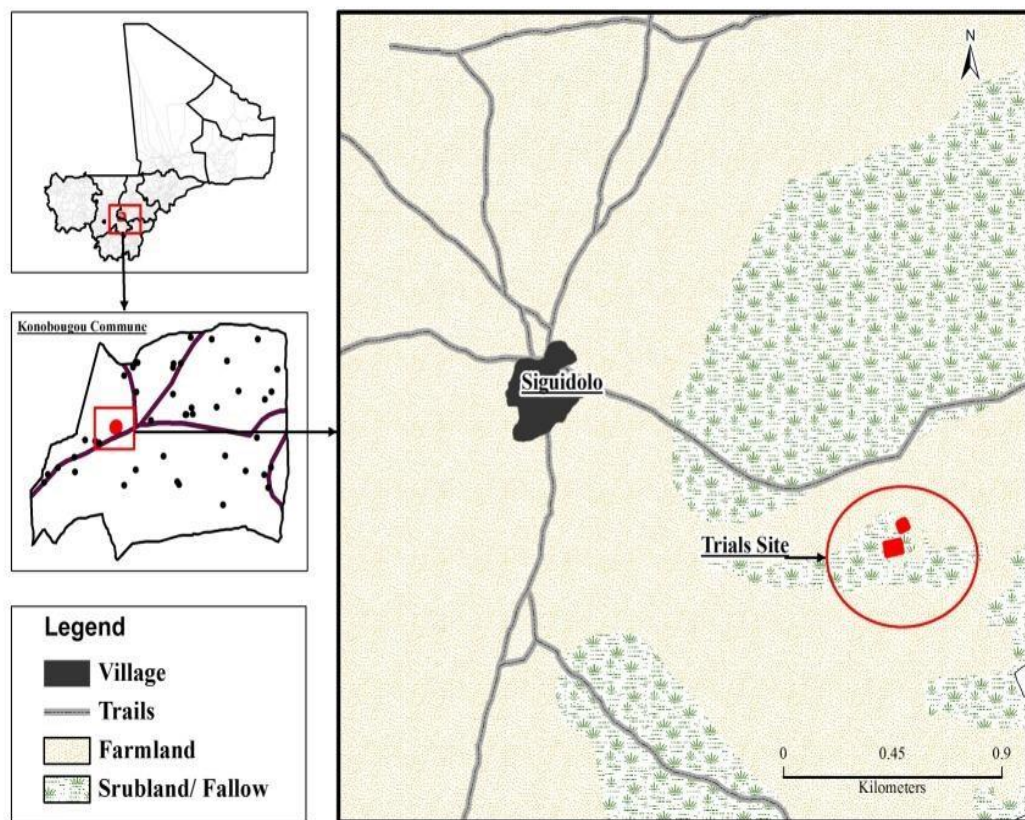


Figure 3.1 Location of the study site (Konobougou)

Soils at Konobougou are mostly loamy *Acrisols*. On the old sandstones, deep *luvisols* present a good porosity all over the soil profile. Water run-off is common, even on soils under grassy fallow (Traore *et al.*, 2004). On cropped fields, up to 20 % or 40 % of total rainfall is often lost through run-off, in spite of the gentle slopes of the landscape (1 to 3%). Soils in the upper part of the slope are affected by soil erosion and loss of basic cations (Traore *et al.*, 2004).

3.2 Study 1: Laboratory evaluation of standard phosphorus requirement (SPR)

for major soils of Mali

Tilemsi phosphate rock is an available local material that can be used to enhance phosphorus availability in soils of Mali. The use of TPR as an integrated soil fertility management (ISFM) product is based on the fact that it is a relatively highly reactive rock phosphate, with a P_2O_5 content of 29 % and it also provides substantial amount of nutrients (Debrah, 2000; Somado *et al.*, 2003).

The laboratory trial was conducted to evaluate the standard phosphorus requirement (SPR) for major soils of Mali, and predict or estimate the amount of Tilemsi phosphate rock needed to meet crop P requirement on such soils. The study was conducted in the Soil Science Laboratory of IER, Sotuba/ Bamako.

Four soil series (suitable for food and fiber productions) were used in this study namely: Longorola, Niessouman, Danga and Konobougou soils. These soils were primarily selected because they are characterized by a range of P levels (Table 3.1). They are also documented and pose a range of texture, organic matter, pH and climatic conditions representative of agricultural soils in Mali.

The properties of the different soils are shown in (Table 3.1). All the soils had low levels of organic carbon. The soils at Longorola and Konobogou had low levels of available soil P, whilst that at Danga and Niessouman had moderate levels of the nutrient. It was also noted that all soils had low clay (<35%) content, except the soil at Longorola which had clay content > 35 %. The pH of the soils ranged from 4.3 to 9.0

while exchangeable Al ranged from 0.03 to 0.43 cmol kg⁻¹, with the highest value recorded with soil from Longorola.

Table 3.1: Characteristics of the soils under study

Chemical properties	Longorola	Danga	Niessoumana	Konobougou
pH(1:1 H ₂ O)	4.30	7.00	9.00	5.02
SOC (%)	2.70	1.23	1.20	1.00
Available P (mg kg ⁻¹)	4.79	10.00	10.80	2.05
Exchangeable cations (cmol ₊ kg ⁻¹)				
Ca	1.03	4.51	6.30	1.32
Na	0.21	2.68	5.46	0.21
K	0.31	0.2	0.2	0.1
Mg	0.55	2.35	3.25	0.70
Al+H	0.43	0.03	0.06	0.03
ECEC	2.53	9.77	15.27	2.36
Ca saturation (%)	40	46.16	41.25	56
Al saturation (%)	17	0.30	0.39	1.27
Particle size distribution (%)				
Clay	45	20	12	4.20
Slit	35	24	20	19.2
Sand	20	56	68	76.5
Texture	Clay	Loam	Sandy loam	Sandy Loam
Classification	Gleysol	Fluvisol	Aeronosol	Acrisols

3.2.1 Evaluation of standard phosphorus requirement

Data for phosphorus sorption was obtained by equilibrating 5 g samples of soils for (7 days) at room temperature in 50 ml of 0.01 M CaCl₂ containing six (6) rates of phosphate as TPR (0, 10, 20, 40, 80, 160 mg L⁻¹) and 2 drops of formol. The mixtures were placed in 50 ml centrifuge tubes and longitudinally shaken on a reciprocating shaker for 30 minutes twice daily (Hue and Fox, 2010). Treatments applied to each soil sample were replicated 4 times in a complete randomized design (CRD). A control

was incubated for each soil and was similarly treated. After the seven days of equilibration, the supernatant was filtered through micropores filter paper (Whatman N° 42). Then, P remaining in solution was determined using Technicon Auto Analyzer II.

The amount of P remaining in soil was assumed as the difference between P initially added and P in the supernatant solution. The quantity of P disappearing from soil solution is considered sorbed (Papini *et al.*, 2000; Hue and Fox, 2010). Phosphorus sorption curves (P remaining in soil solid vs. P in solution) were constructed from these data. The amount of P remaining in soil to give a solution concentration of 0.2 mg P L⁻¹ was referred to as the standard P requirement (SPR) as suggested by Hue and Fox (2010).

3.2.2 Evaluation of sorption data

The linear form of the Langmuir surface equation was used to calculate parameters that are indices of the capacity for, and the intensity of, P sorption by the soil. The Langmuir model was selected because of its simplicity for estimating P sorption maxima and sorption affinity constant. The Langmuir equation is written as:

$$X = \frac{(K_L \cdot X_m \cdot C)}{(1 + K_L \cdot C)}$$

Where: C = concentration of P in equilibrium solution (mg P mL⁻¹), X = amount of P remaining in soil (mg P kg⁻¹ soil), X_m = sorption maximum (mg P kg⁻¹ soil), and K_L = coefficient related to bonding energy. The sorption maximum (X_m) was calculated from the reciprocal of the slope (X_m = 1/ slope) of the adsorption isotherms. This parameter reflects the magnitude of sorption sites available for P adsorption.

3.2.3 Data analysis

Relationships between P sorption parameters and P remaining in soil to obtain solution P concentration of 0.2 mg L^{-1} with selected soil chemical properties were analyzed with correlations and tested for significance at $P = 0.05$ using GenStat statistical software (9th edition, 2006).

3.3 Study 2: Field assessment of the efficiency of Tilemsi rock phosphate compared to DAP at different rates of application under different tillage practices

Soils of Mali are characterized by their low levels of available phosphorus. Farmers rely on the use of organic matter to improve soil fertility and crop yield. However, organic matter is not available in sufficient amounts because of competing alternative uses. Water soluble phosphate (WSP) and rock phosphate are recognized as the most efficient to correct soil phosphorus problem. Water soluble phosphate is not applied as ISFM product by poor farmers because of its associated high price. Even though TPR is recognized as ISFM product, its usage is still limited to farmers because of its relatively low solubility.

The field experiment was carried out to evaluate the interaction of phosphorus standard P requirement rate, and actual TPR recommended rate under two tillage practices: contour ridge (CR) and hoe tillage (HT) as a control on some selected soil properties and maize growth and yield.

3.3.1 Soils of the study site

The study was conducted at Konobougou on a plot of land which had been under fallow since 2005 due to severe soil degradation problem (Hydric and wind erosion).

Some chemical and physical properties of the soils for the study area are presented in Table 3.2. Landon's (1996) guidelines were used to interpret the results of the soil analyses. The soils under the maize and sorghum are loamy sands classified as *Ultisols* (USDA, 1999). The pH of the soils under both maize and sorghum was very strongly acidic (Table 3.2). The amounts of organic carbon, nitrogen and phosphorus content of the soils under both crops were low with very low effective cation exchange capacities. The fertility and productivity status of the soils will therefore be enhanced by the addition of soil amendments.

Table: 3.2 Chemical properties and texture of the soils used for maize and sorghum cultivation

Chemical properties	Maize	Sorghum
pH (1:1 H ₂ O)	4.70	4.15
SOC (%)	0.40	0.30
Total nitrogen (%)	0.02	0.01
Available P (mg kg ⁻¹)	2.13	3.78
Exchangeable cations (cmol ₊ kg ⁻¹)		
Ca	0.85	0.7
K	0.10	0.08
Na	0.21	0.016
Mg	0.40	0.43
Al+H	0.06	0.09
ECEC	1.62	1.31
Particle size distribution (%)		
Sand	76.5	73.55
Silt	19.2	21.78
Clay	4.20	4.67
Texture	Sandy loam	Sandy loam

3.3.2 Experimental design

The experiment was initiated in 2013 and terminated in 2014. The trial was a factorial combination of two (2) tillage practices (CR and HT) and three (3) rates of phosphorus

0 kg ha⁻¹ (control), 11 kg ha⁻¹ (recommended rate of TPR application) and 16 kg ha⁻¹ (standard phosphorus requirement for the study soil). The phosphorus was applied as DAP, TPR powder form and TPR pellet form, and No P applied as control arranged in a randomized complete block design (RCBD) with three replications.

3.3.3 Land preparation

Animal drawn mould board ploughs and tine harrows were used to prepare the contour ridge plots for seeding. The main contour ridge was made by the use of “niveau a eau”. The other plots were subjected to hoe tillage as the prevalent local tillage.

3.3.4 Fertilizer application

Tilemsi phosphate rock (TPR) pellet, powder and DAP were applied at 0 kg of P ha⁻¹, 11 kg of P ha⁻¹ (recommended rate) and 16 kg of P ha⁻¹ (standard phosphorus requirement for Konobougou soil) and KCl at 30 kg ha⁻¹ (recommended rate) incorporated into the surface prior to planting (homestead fertilizer) . Urea was applied at 150 kg ha⁻¹ in splits to respective plots (50-50-50 kg ha⁻¹) at 2, 4 and 6 week after planting. To balance the rate of nitrogen in the DAP (80 kg i.e. 14 kg of N) the same amount was calculated from urea and was applied to other plots except for the absolute control plot.

3.3.5 Planting material

Seeds of Sotubaka maize variety were obtained from the “Programme Maïs” of Sotuba research center (IER). The optimum grain yield of sotubaka is 3.5 to 4 t ha⁻¹ and growth period is between 90 and 100 days.

3.3.6 Plant culture

The maize seeds were sown using hoes at spacing of 50 cm x 70 cm within the incorporation zone of fertilizer (2-7 cm beneath the soil surface). Four seeds were sown per hill and seedlings thinned to two per hill two weeks after germination.

3.3.7 Weed control

Weed control was done manually by hoeing. Two weeding regimes were observed at 2nd and 7th week after planting.

3.3.8 Soil sampling and laboratory analysis

Soil sampling was done by using the auger. A composite of four soil samples were taken at 0-20 cm depth before fertilizer phosphate application and after harvest on each experimental units. Soil samples were air dried and then sieved through a mesh of 2 mm diameter. The sieved samples were stored in polythene bags for chemical and physical analyses. The analyses was done at the soil water and plant laboratory (*united analyse*) of IER /Sotuba.

3.3.8.1 Determination of soil pH

The soil pH was determined by the potentiometric method (1:1 soil: water ratio) proposed by Mclean, (1982). A 50 g dried soil was weighed into a plastic flask and 50 ml distilled water added. The mixture was thoroughly shaken on a reciprocating shaker for one hour. Just before measuring pH, the bottles were shaken by hand. The pH meter was standardized with buffer solutions of pH 4.0 and 7. After standardization, the electrode of pH meter was inserted into the upper part suspension and the pH read.

3.3.8.2 Determination of organic carbon

Soil organic C was determined by the modified Walkley-Black wet oxidation method as outlined by Nelson and Sommers (1982). Two grams (2.00 g) of soil was weighed into 500 ml conical flask and 10 ml of 0.166 M (1.0 N) $K_2Cr_2O_7$ solution added, followed by 20 ml concentration H_2SO_4 and allowed to cool on an asbestos sheet for 30 minutes. Two hundred milliliters of distilled water was added followed by 10 ml of H_3PO_4 and then 1.0 ml of diphenylamine indicator solution. This mixture was then titrated with 1.0 M ferrous sulphate solution until the colour changed from a blueblack colouration to a permanent greenish colour. A blank determination was carried out in a similar fashion in every batch of samples analysed without soil.

Calculation:

$$\%C = \frac{N \times (V_{bl} - V_s) \times 0.003 \times 1.33 \times 100}{g}$$

where :

N= Normality of $FeSO_4$ solution

V_{bl} = ml of $FeSO_4$ used for blank V_s = ml

of $FeSO_4$ used for sample titration g=

mass of soil taken in gram

0.003= mili-equivalent weight of C in grams (12/4000)

1.33= correction factor used to convert the wet combustion C value to the true C value since the wet combustion method is about 75 % efficient in estimating C value, (i.e. $100/75=1.33$).

3.3.8.3 Determination of total nitrogen

A 0.5 g of fine air-dried soil was weighed into a 50 ml volumetric flask. A 0.75 g of catalyst (1.55 g of Se + 1.55 g of $CuSO_4$ + 96.9 g of Na_2SO_4), some carborundum grains and 5 ml of concentrated sulphuric acid were added. The mixture was stirred

and the flask was placed on a hot plate and heated to 200 °C for 1 hour. The mixture was continuously heated to 350 °C, until a clear colour or pale green colour appeared. The flasks were removed from the plate and allowed to cool. Slowly, about 25 ml of distilled water was added in small portions. When the mixture was cooled, the volume was made up to 50 ml with distilled water and mixed well. Clear aliquot of sample and blank were pipetted and put in the tube of auto-analyzer

Technicon for determination of total nitrogen at sensitivity 6.00 to 50 mV.

Calculation:

$$\% \text{ Total N} = \frac{(a - b) \times 50}{\text{weight of sample (g)} \times 10000}$$

where:

a = N in soil sample b

= N in blank

1000 = coefficient of conversion from ppm N to percentage N

50 ml = final diluted volume of digest

3.3.8.4 Determination of available P

The available phosphorus was extracted with Bray I extracting solution (0.03 M NH₄F and 0.025 M HCl) as described by Olsen and Sommers (1982). Phosphorus in the extract was determined by the blue ammonium molybdate method with ascorbic acid as the reducing agent using a spectrophotometer auto analyzer. A 2 g soil sample was weighed into a shaking test tube (20 ml) and 14 ml of extracting solution of Bray-1 added. The mixture was shaken for 1 minute on a reciprocating shaker and filtered through a Whatman No. 42 filter paper. An aliquot of the blank and the extract were

pipetted into separate test tubes and placed in auto analyzer sampler. A standard series of 0, 1.5, 3, 4.5 and 6 mgP/L was prepared from 20 mg/L phosphorus. The concentration of P was measured in the standard series, samples and blanks on Technicon Auto Analyzer, manifold P Bray at sensitivity 1.00 to 50 mv.

Calculation:

$$\text{Available P (mg kg}^{-1}\text{)} = 7 \times (a - b)$$

where:

$$a = \text{mg kg}^{-1} \text{ P measured for the sample}$$

$$b = \text{mg kg}^{-1} \text{ P measured for blank}$$

$$7 = \text{volume of Bray-1 extracting solution}$$

3.3.8.5 Determination of exchangeable basic cations

The exchangeable bases were measured using the ammonium acetate method as described by Rhoades (1982). A 2.5 g of dried soil was taken into 100 ml centrifuge tube and 50 ml of 1.0 M ammonium acetate solution having pH 7.0 added to it. The mixture was shaken for 30 minutes. The solution was centrifuged until the supernatant liquid was clear and the extract collected into volumetric flask of 50 ml. Ammonium acetate was then used to dilute the solution to 50 ml and the concentration of Ca, Mg, K and Na read from Agilent 4100 Microwave Plasma-Atomic Spectrometer (Agilent 4100-MP-AES).

Calculations:

$$\text{Na (cmol}_+ \text{/kg)} = \frac{100 \text{ g} \times 50 \text{ ml} \times (a - b)}{23 \times 1000 \text{ ml} \times \text{weight of sample}}$$

$$K \text{ (cmol}_+/\text{kg)} = \frac{100 \text{ g} \times 50 \text{ ml} \times (a - b)}{39.1 \times 1000 \text{ ml} \times \text{weight of soil sample}}$$

$$Ca \text{ (cmol}_+/\text{kg)} = \frac{100 \text{ g} \times 50 \text{ ml} \times (a - b)}{20 \times 1000 \text{ ml} \times \text{weight of soil sample}}$$

$$Mg \text{ (cmol}_+/\text{kg)} = \frac{100 \text{ g} \times 50 \text{ ml} \times (a - b)}{12 \times 1000 \text{ ml} \times \text{weight of soil sample}}$$

where:

23 = equivalent mole of Na

39.1 = equivalent mole of K

20 = equivalent mole of Ca

12 = equivalent mole of Mg

100 = weight of sample for conversion to meq/100

50 ml = volume of diluted

solution 1000 ml = initial volume

a = cmol/kg for sample b =

cmol/kg for blank

3.3.8.6 Determination of exchangeable acidity

The exchangeable acidity was measured using the potassium chloride method as described by Thomas (1982). A 10 g of soil sample was weighed and 25 ml of 1.0 *M* KCl solution was added. The mixture was shaken on a reciprocating shaker for 30 minutes and filtered into a 250 ml Erlenmeyer flask followed with an additional

volume of 125 ml of 1.0 *M* KCl in 25 ml increments to a total of 150 ml. A blank was also included in the titration. About 4-5 drops of phenolphthalein indicator solution was added. The solution was titrated with 0.1 *M* NaOH until the colour just turned permanently pink.

Calculation:

$$\text{Exchangeable acidity (cmol}_+/\text{kg)} = \frac{\text{ml NaOH sample} - \text{ml NaOH blank}}{\text{g sample}} \times M \times 100$$

where:

M = Molarity of NaOH

The ECEC was estimated by summing the exchangeable basic cations and exchangeable acidity (Mc Lean, 1982).

3.3.8.7 Determination of particle size distribution

The hydrometer method was used to analyze the soil particle size (Anderson and Ingram, 1993). The weight of 51 g of air – dry soil (< 2 mm) was transferred into a 250 ml beaker. A 50 ml sodium hexametaphosphate (calgon) solution was dispensed into the soil together with 100 ml of deionized water. The suspension was vigorously stirred for 1 min using a glass rod and allowed to stand undisturbed for 30 minutes before transferring to the mixer for mixing using medium speed for 15 minutes. After mixing, the suspension was transferred to the sedimentation cylinder and plunged.

The mixture was made up to 1000 ml with deionized water and plunged vigorously. This was immediately continued by placing the soil hydrometer and sliding it slowly into the suspension until it floated, noting the time. The first hydrometer (*H*₁) and temperature (*T*₁) readings at 40 seconds were recorded. Duplicate readings were

taken. After the first two readings of hydrometer (H_1) and temperature, the suspension was allowed to stand undisturbed for 3 hours before the second hydrometer readings (H_2) and the temperature of the suspension (T_2) were taken.

Calculation:

$$\% \text{ Sand} = [100 - (H_1 + 0.2) \times (T_1 - 20) - 2] \times 2$$

$$\% \text{ Clay} = [(H_2 + 0.2) \times (T_2 - 20) - 2] \times 2 \%$$

$$\text{Silt} = 100 - (\% \text{ sand} + \% \text{ clay})$$

where

H_1 = average of first two hydrometer readings

T_1 = average of first two temperature readings

H_2 = second hydrometer reading

T_2 = second temperature reading

3.3.9 Analysis of plant materials

3.3.9.1 Determination of phosphorus and nitrogen

Plant samples were wet digested following the procedure described by Nelson and Sommers, (1980). A 0.5 g of the dried plant material was taken into 50 ml volumetric flask and 2.5 ml of concentrated sulphuric acid and one ml of hydrogen peroxide were added. The mixture was swirled and placed on hot plate and heated at 270 ° C for 10 minutes. The flask was removed from the plate and allowed to cool for 10 minutes after which 1.0 ml H_2O_2 was added and heated for 10 minutes at the same temperature. Heating, cooling and addition of 0.5 ml of H_2O_2 were undertaken still a colorless was observed. The solution was removed from the hot plate and the volume was made up to 50 ml with distilled water and the digest used to determine N and P.

Determination of nitrogen

Total nitrogen was measured using the Technicon Auto Analyzer.

Calculation :

$$\% \text{ Total N} = \frac{(a - b) \times 50}{\text{Weight of plant sample} \times 10000}$$

where

a = N for plant sample

b = N for blank

10000 = coefficient of conversion from ppm N to percentage N

50 ml = final diluted volume of digest

Determination of phosphorus

Total phosphorus was determined using the Technicon Auto Analyzer, manifold P Bray-1.

Calculation :

$$\% \text{ P} = \frac{(a - b) \times 50}{\text{Weight of plant sample} \times 10000}$$

where :

a = P for plant sample

b = P for blank

50 ml = final diluted volume of digested and

10000 = coefficient of conversion from ppm to percentage P

3.3.10 Harvesting

Maize was harvested at physiological maturity. Three middle rows from each plot were harvested to evaluate grain yield and above ground biomass. The harvested area was 4.2 m².

3.3.11 Parameters measured

Grain yield per plot was converted to kg ha⁻¹ using the formula:

$$\text{Grain yield (kg ha}^{-1}\text{)} = \text{kg grain yield m}^{-2} \times 10,000\text{m}^2.$$

Above ground biomass per plot was also converted to kg ha⁻¹ using the formula:

$$\text{Biomass yield (kg ha}^{-1}\text{)} = \text{kg Biomass yield m}^{-2} \times 10,000\text{m}^2.$$

The following were computed from the grain yield data:

Relative agronomic efficiency (RAE): the relative agronomic efficiency (RAE) was computed as the ratio of the yield responses with test fertilizer (TPR) to the respective yield responses of the reference fertilizer (DAP) at the same rate (11 kg P ha⁻¹ and 16 kg P ha⁻¹).

$$\text{RAE} = \frac{Y_{\text{TPR}} - Y_{\text{Control}}}{Y_{\text{DAP}} - Y_{\text{Control}}} \times 100$$

Where Y is the maize yield in response to the various treatments.

The agronomic efficiency (AE): the agronomic P use efficiency was calculated as the yield obtained from the P (Y_P) fertilized plot minus control (Y_C), divided by a unit weight of the applied P fertilizer (P_w). Agronomic efficiency of P is defined as kg yield increase per kg P applied.

$$\text{AE} = \frac{Y_P - Y_C}{P_w}$$

Partial factor productivity (PFP) was calculated as the yield obtained from the P (YP) fertilized plot divided by a unit weight of the fertilizer applied.

$$\text{PFP} = \frac{\text{Corn grain yield (kg/ha)}}{\text{Fertilizer applied (kg p/ha)}}$$

Phosphorus recovery efficiency (PRE): the PRE was calculated as the phosphate removed from the P fertilized plot minus phosphate removed from the control plot divided by a unit of the applied P fertilizer.

$$\text{PRE} = \frac{(\text{Total P uptake with fertilizer}) - (\text{Total P uptake with control})}{\text{Fertilizer applied}} \times 100$$

All the different parameters such as AE, PFP and PRE were determined based on the formula developed by Dobermann, (2005)

3.3.12 Estimation of nutrient uptake

For the evaluation of the general nutrient uptake, grains, leaves and stem samples were selected for total elemental analysis (N and P). Phosphorus uptake was computed from the data as the product of nutrient concentration in grain or biomass multiplied by the yield.

Nutrient uptake = dry weight x concentration of nutrient (N/ P) in plant (grain or biomass)

3.3.13 Assessment of gravimetric soil water content

Gravimetric water content was measured by sampling soil at three (3) different periods: 4, 8 and 12 weeks after planting both on contour ridge plot and hoe tillage plot. Twelve soil moist samples were collected on each repetition by tillage practice plot at each sampling time.

Soil sampling was done using auger at two (2) depths: 0 - 10 cm and 10 - 20 cm. The soil moisture content or water mass was determined by drying the moist soil sample

(W_{tm}) to constant weight (105 °C at 24 hours) and measuring the soil mass after and before drying (W_{td}). The water mass (or weight) was estimated as the difference between the weights of the wet and oven dry samples (De Angelis, 2007).

The moisture content on dry weight (W_{td}) basis was calculated using the formula:

$$g = \frac{(W_{tm} \text{ of soil} + \text{tare}) - (W_{td} \text{ of soil} + \text{tare})}{(W_{td} \text{ of soil} + \text{tare}) - (\text{tare})}$$

3.3.14 Economic analysis

The economic analysis of the application of the different rates of phosphate (DAP and TPR) under CR and HT was based on the evaluation of the value cost ratio (VCR).

The unsubsidized input costs and the crop peak prices were used to calculate the VCR as an indicator of acceptability of investment, using the formula:

$$VCR = \frac{Y - Y_c}{X}$$

where Y is the value of the crop in intervention plots, Y_c is the value of the crop harvested in control plots, and X is the cost of inputs (seed and fertilizers)

3.4 Study 3: Field assessment of the response of high yielding sorghum variety to different forms of Tilemsi rock phosphate

Several ways had been used to improve TPR availability under the short-term conditions in fields. The most relevant is the partial acidulation of phosphate rock (PAPR). Even though PAPR is efficient to enhance TPR solubility, its use is still limited because of the high cost of acid used. Togouna Agro Industry (fertilizer producer industry) has developed different kinds of TPR combined with nitrogen fertilizer such as (NH₄)₂SO₄ and TPR combined with KCl.

The field trial was conducted to evaluate the effect of the different forms of TPR on sorghum growth and yield and some selected soil properties.

3.4.1 Soil of the study site

The experiment was conducted at Konobougou located at 12° 55'N 6°46'W within the Sahelian zone of Mali during the 2012 - 2013 and 2013 - 2014 cropping season.

The soil used for the study is described in section 3.3.1.

3.4.2 Experimental design

The experiment was laid out in a randomized complete block design with 3 replicates.

The trial was a factorial combination of four (4) types of Tilemsi PR such as TPR pellet, pellet with KCl + (NH₄)₂SO₄, pellet with KCl and pellet with (NH₄)₂SO₄ and three levels of P (0 kg ha⁻¹ P; 11 kg ha⁻¹ P; 16 kg ha⁻¹ P) .

3.4.3 Phosphate rock

The blends of phosphate rock used in this study were obtained from Toguna Agro Industry. The chemical composition of the different blends of TPR is shown in Table 3.3.

Table: 3.3 Forms of Tilemsi phosphate rock used from Toguna Agro Industry

Blends of TPR	Ratio (%)			Formula
	TPR	(NH ₄) ₂ SO ₄	KCl	N-P-K
TPR+KCl	70	-	30	0-20 -18
TPR+(NH ₄) ₂ SO ₄	70	30	-	7-18-0
TPR+KCl+(NH ₄) ₂ SO ₄	70	20	10	4-20-6
Sole TPR	100	-	-	0- 11- 0

3.4.4 Planting material

Sorghum (*Sorghum bicolor*) was obtained from the seed research program of CRRA de Sotuba /IER. The variety was CSM 65 (*Djakumbe*). The potential yield of the variety ranges from 900 kg to 1200 kg ha⁻¹ and the growing period is between 90 and 100 days.

3.4.5 Plant culture

Sorghum (*Sorghum bicolor*) was sown using a hand hoe at spacing of 70 cm x 50 cm within the incorporation zone of fertilizer (2-7 cm beneath the soil surface). Four to six seeds were sown per hill and thinned to two plants per hill two weeks after planting.

3.4.6 Weed control

All plots were kept weed free by hand weeding during the growing season at 2nd and 7th weeks after planting.

3.4.7 Fertilizer application

All the applied nutrients: TPR pellet, pellet with KCl (P+K), pellet with (NH₄)₂SO₄ (P+SAM), pellet with KCl+ (NH₄)₂SO₄ (P+K+SAM) were broadcasted and incorporated into the soil by hand cultivation prior to planting.

3.4.8 Soil sampling and laboratory analysis

The soil sampling and laboratory analysis were done according to the procedure used in section 3.3.8.

3.4.9 Harvesting

At crop maturity, the two middle rows of each plot were harvested to evaluate grain yield and above ground biomass. The harvested area was 3.5 m².

3.4.10 Parameters measured

The following parameters were computed from the data according to the procedure used in section 3.3.11. The parameters were: grain yield, biomass yield, agronomic efficiency (AE), partial factor productivity (PFP) and phosphate recovery efficiency (PRE).

3.4.11 Crop growth rate

Five plant samples from each plot were randomly harvested for growth analysis at 3, 6 and 9 weeks after planting (WAP). Samples were oven-dried at 80 °C for 72 h until constant dry weights were obtained. Crop growth rate (C) was calculated using the following formula as proposed by Gardener *et al.* (1985):

$$\text{CGR}(\text{g m}^{-2} \text{ d}^{-1}) = \frac{W_2 - W_1}{T_2 - T_1}$$

where W_1 and W_2 are dry weights taken on two successive occasions at T_1 and T_2 , respectively.

3.4.12 Plant height

At physiological maturity, 10 plants were randomly selected from the middle rows of each plot and measured to evaluate crop height from each experimental unit.

3.4.13 Phosphorus partial balance

The soil phosphorus partial balance (ΔP) was determined by the difference between added and exported nutrients.

$$\Delta P = \text{Input of P (mineral fertilizer)} - \text{uptake (removal in grain and straw)}$$

3.4.14 Plant sample analysis

For the evaluation of the general nutrient uptake, grain leaf and stem samples from the sixteen treatments were sampled for total elemental analysis. The selected samples were air dried, grounded and passed through 1 mm mesh sieve and mixed thoroughly. Phosphorus uptake was computed from the data according to method described in section 3.3.12

3.4.15 Data analysis

All data was subjected to the Analysis of Variance (ANOVA) using the Genstat statistical package (9th edition, 2006). The least significant difference (LSD) Duncan test procedure was used to compare treatment means at 5 % probability. Correlation and regression analyses were carried out between measured soil and plant parameters at harvest.

CHAPTER FOUR

4.0 RESULTS

4.1 Study 1: Laboratory evaluation of standard phosphorus requirement for major soils of Mali

4.1.1 Phosphate sorption isotherm

The standard phosphorus requirement (SPR) in soil solution varied widely between the studied soils (Table 4.1). The SPR value for Danga was 12 mg P kg⁻¹ while Longorola soil with clay content of 45 % produced SPR of 24 mg P kg⁻¹. The sandy soils of Niessoumana and Konobougou needed 10 to 7.10 mg P kg⁻¹, respectively to maintain 0.2 mg L⁻¹ of P in soil solution.

The amounts of TPR required (according to the SPR values) varied between 16 to 54 kg of P ha⁻¹. These values recorded in this study were higher than the recommended dose (11 kg of P ha⁻¹) of TPR used for all the soils under study.

Table 4.1. Standard phosphorus requirement and amounts of TPR required for the soils under study

Soil series	SPR (mg/kg)	TPR required (kg/ha)
Longorola	24.00	53.76
Danga	12.00	26.88

Niessoumana	10.00	22.40
Konobougou	7.10	16.00

SPR= Standard phosphorus requirement

The linearized Langmuir sorption model described adequately the sorption behaviour ($R^2 \geq 0.78$) for all the soils under study (Table 4.2). Sorption isotherms for the four soils showed that the soils differed considerably in sorption characteristics. Sorption maxima ranged from 59 to 200 mg P kg⁻¹ while sorption affinity constant ranged from 0.30 to 1.66 L mg⁻¹ (Table 4.2).

Table 4.2: Phosphorus sorption characteristics of the different soils

Soil series	Linearized Langmuir equations	X max (mg kg ⁻¹)	K _L (L mg ⁻¹)	r ²
Longorola	Y=0.005x+0.003	200	1.66	0.79
Danga	Y=0.006x+0.020	166	0.30	0.78
Niessoumana	Y=0.006x+0.007	167	0.85	0.98
Konobougou	Y=0.017x+0.030	59	0.56	0.89

Xmax = sorption maxima, K_L= sorption affinity constant, r²= coefficient of regression

4.1.2. Relationship between P sorption characteristics and soil properties

Exchangeable acidity, clay and OM content were positively correlated with phosphorus sorption characteristics (Xmax and K_L) (Table 4.3). Exchangeable acidity was positively correlated with the sorption affinity constant ($r = 0.95$) and P_{SPR} ($r = 0.97$). Similarly, OM was positively correlated with the sorption affinity constant ($r = 0.91$), P_{SPR} ($r = 0.98$) and sorption maxima ($r = 0.67$). The same trend was observed with clay. Soil clay content was positively correlated with P_{SPR} (0.99), sorption maxima ($r = 0.78$) and sorption affinity constant ($r = 0.79$) (Table 4.3). However, pH was negatively correlated with P_{SPR} ($r = -0.51$) and the sorption affinity ($r = -0.44$). There was a positive but weak relationship between pH and sorption maxima ($r = 0.19$).

Table 4.3 Correlation coefficients describing relationships between P sorption characteristics and selected soil properties

Properties	Properties											
	Exch. ac	Exch. Ca	Clay	Exch. K	Exch. Na	OM	P(SPR)	P Bray1	Sand	Silt	Xmax	K _L
Exch. Ca	-0.544											
Clay	0.928	-0.365										
Exch. K	0.853	-0.079	0.951									
Exch. Na	-0.458	0.983	-0.334	-0.030								
OM	0.933	-0.492	0.967	0.899	-0.423							
P (SPR)	0.965	-0.427	0.993	0.935	-0.379	0.98						
P Bray 1	-0.297	0.929	-0.033	0.234	0.891	-0.214	-0.116					
Sand	-0.936	0.405	-0.990	-0.937	0.374	-0.972	-0.995	0.075				
Silt	0.947	-0.493	0.990	0.900	-0.426	0.976	0.992	-0.170	-0.955			
Xmax	0.593	0.291	0.784	0.925	0.313	0.666	0.736	0.585	-0.757	0.685		
K_L	0.946	-0.428	0.794	0.779	-0.294	0.912	0.854	-0.271	-0.798	0.802	0.534	
pH	-0.590	0.990	-0.458	-0.170	0.988	-0.555	-0.507	0.869	0.456	-0.579	0.190	-0.437

Exch.ac : Exchangeable acidity; Exch.ca: Exchangeable calcium; Exch.K: Exchangeable potassium; Exch Na: Exchangeable sodium

53
KNUST



4.2 Study 2: Assessment of the efficiency of Tilemsi rock phosphate compared to DAP at different rates of application under different tillage practices

4.2.1: Effects of tillage practices and soil amendments on soil chemical properties

4.2.1.1: Soil pH

Soil pH was not significantly ($P > 0.05$) affected by tillage practices in both cropping seasons (Tables 4.4 and 4.5). Though not significant, soil pH was slightly higher under CR than HT ranging from 4.38 to 4.41 and 4.71 to 4.76, respectively in 2013 and 2014. The application of soil amendments as TPR and DAP influenced significantly ($P < 0.01$) soil pH values. The pH recorded on TPR amended plots was higher than values recorded on DAP and no acontrol plots. The decreasing order of the impact of phosphorus fertilizer on soil pH was TPR pellet > TPR powder > DAP > control in 2013. A similar trend was observed in 2014 except that TPR powder produced slightly higher pH value than the pellet form. The interaction between phosphorus type and phosphorus rate of application significantly influenced ($P < 0.05$) soil pH during the two growing seasons (Tables 4.4 and 4.5).

A somewhat constant increase in soil pH was observed with increased P application rate in 2013 with powdered TPR (Figure 4.1). For TPR pellet form, a decline in soil pH was observed followed by a slight increase from 11 to 16 kg P ha⁻¹ (Figure 4.1). The trend observed with the DAP was similar to that of the control. There was an increase in soil pH from P₀ to 11 kg P ha⁻¹ after which it declined from P applied at 11 to 16 kg ha⁻¹ (Figure 4.1).

No significant differences were observed in soil pH among the different phosphorus sources at 0 and 11 kg ha⁻¹, while significant difference was observed at P applied at 16 kg ha⁻¹ with TPR in powder form compared to DAP and the control (Figure 4.1). At the 16 kg P ha⁻¹ rate, a significant difference was observed between TPR pellet compared to the control, while no significant difference was observed between TPR powder and pellet form (Figure 4.1). In 2014, there was an increase in soil pH for all phosphorus sources with increased P application (Figure 4.2). No significant differences ($P > 0.05$) were observed in soil pH among the different phosphorus types at 0 P, however significant differences were observed when the different types of phosphorus (TPR and DAP) applied were compared to the control at both P applied at 11 and 16 kg ha⁻¹. Tilemsi phosphate rock in powder form produced significantly higher value ($P < 0.05$) than DAP at both 11 and 16 kg P ha⁻¹ (Figure 4.2). The pH recorded at harvest was slightly higher under DAP and TPR amendments at 11 and 16 kgP ha⁻¹ than the initial pH value (4.70) in 2014 (Figure 4.2).

Table 4.4 Effects of soil amendments and tillage practices on soil pH, SOC, total N and available P in 2013

	pH	C (%)	N (%)	P (mg/kg)
Tillage Practice (TP)				
CR	4.41	0.31	0.01	5.26
HT	4.38	0.36	0.01	3.81
Fpr	0.55	0.06	0.23	0.01
Phosphorus Type (PT)				
Control (No-P)	4.25	0.35	0.01	3.12
DAP	4.29	0.32	0.01	6.67
TPR (Pellet)	4.59	0.36	0.01	4.13
TPR (Powder)	4.54	0.33	0.01	4.55
Lsd (0.05)	0.21	0.06	0.003	0.85
Fpr	0.01	0.58	0.98	< 0.001
Phosphorus Rate (PR) kg/ha				
0	4.26	0.36	0.01	3.10
11	4.38	0.34	0.01	4.63
16	4.54	0.31	0.01	6.13
Lsd (0.05)	0.18	0.05	0.002	0.74
Fpr	0.01	0.18	0.12	< 0.001
Interactions				
PT x PR	0.05	0.09	0.06	< 0.001
TP x PT	0.40	0.28	0.42	0.002
TP x PR	0.27	0.02	0.01	0.01
TP x PT x PR	0.33	0.58	0.34	0.02
CV (%)	7.20	28.30	41.40	28.10

TP: Tillage practice PT: Phosphorus Type; PR: Phosphorus rate

Table: 4.5 Effects of soil amendments and tillage practices on soil pH, SOC, total N and available P in 2014

	pH	C (%)	N (%)	P (mg/kg)
Tillage Practice (TP)				
CR	4.76	0.23	0.02	4.25
HT	4.71	0.25	0.02	3.96
FPr	0.13	0.96	0.73	0.25
Phosphorus Type (PT)				
Control (No-P)	4.20	0.26	0.01	2.73
DAP	4.72	0.27	0.02	4.69
TPR (Pellet)	4.98	0.28	0.02	4.11
TPR (Powder)	5.03	0.27	0.02	4.61
Lsd (0.05)	0.20	0.07	0.001	0.46
FPr	< 0.001	0.45	<0.001	<0.001
Phosphorus rate (PR) kg/ha				
0	4.33	0.25	0.01	2.25
11	4.89	0.20	0.02	4.79
16	4.98	0.25	0.03	5.28
Lsd (0.05)	0.17	0.06	0.003	0.40
FPr	<0.001	0.23	<0.001	<0.001
Interactions				
PT x PR	0.002	0.95	0.91	<0.001
TP x PT	0.02	0.62	0.64	0.01
TP x PR	0.29	0.89	0.08	<0.001
TP x PT x PR	0.44	0.72	0.19	0.06
CV	6.30	47.50	23.00	16.90

TP: Tillage practice PT: Phosphorus type; PR: Phosphorus rate

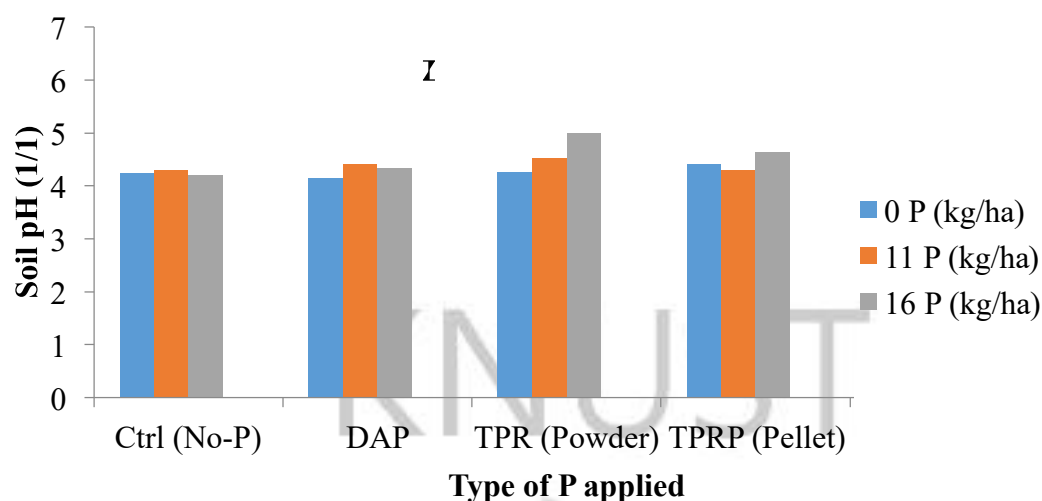


Figure 4.1: Interaction effects of phosphorus type and application rate on soil pH

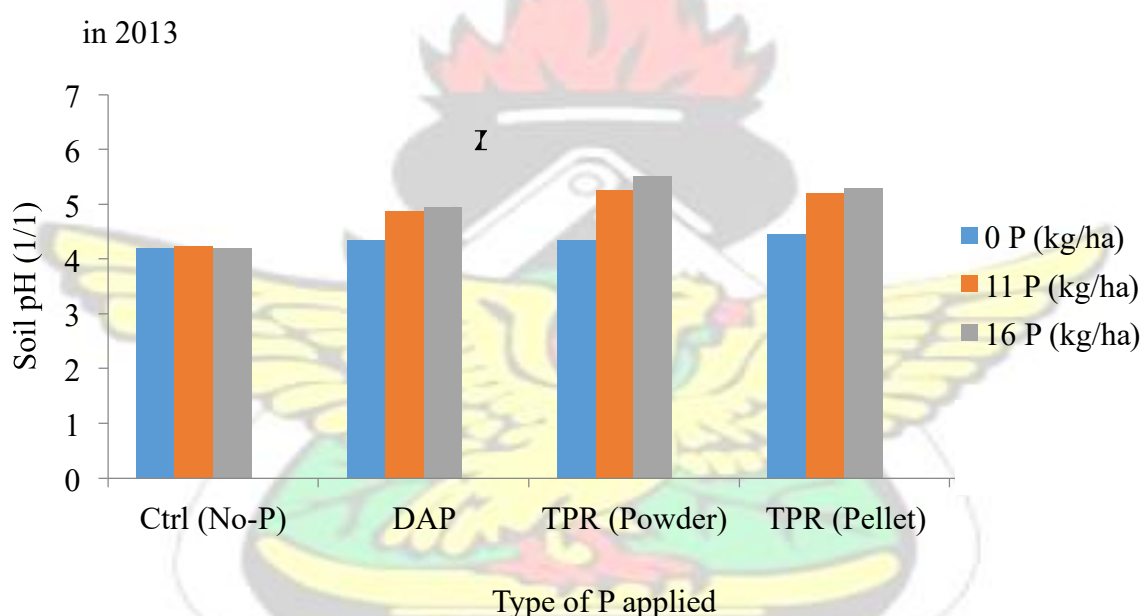


Figure 4.2: Interaction effects of phosphorus type and application rate on soil pH in 2014

4.2.1.2: Soil organic carbon

In this study, tillage practices did not affect significantly the soil organic carbon (SOC) contents in both seasons (Tables 4.4 and 4.5). The types and rates of phosphorus applied did not also significantly ($P > 0.05$) influence SOC in both cropping seasons (Tables 4.4 and 4.5). The SOC recorded in 2014 was significantly lower than that of 2013 as shown by year effect analysis (Appendix 2a) and the initial value. The

interaction among type of tillage practice and P application rate did not have any significant impact on SOC in the two growing seasons.

4.2.1.3: Soil total N

Soil total N was not significantly ($P > 0.05$) influenced by tillage practices during the two growing seasons (Tables 4.4 and 4.5). Both the type and rate of phosphorus applied did not show significant effect on soil total N in 2013, however the two parameters significantly ($P < 0.001$) influenced soil total N in 2014.

Tilemsi phosphate rock and DAP amended plots produced significantly ($P < 0.001$) higher N value than the control plot, while no significant difference was observed between them (Table 4.5).

Considering the phosphorus application rate, N was significantly higher in plots treated with 11 and 16 kg ha⁻¹ P than the control, and P applied at 16 kg ha⁻¹ had significantly higher N value than P applied at 11 kg ha⁻¹ (Table 4.5). The soil total N recorded in 2014 was higher than that of 2013 as shown by year effect analysis (Appendix 2a) and the initial value.

4.2.1.4: Soil available P

Soil available phosphorus was significantly ($P < 0.01$) affected by tillage practices in 2013 (Table 4.4) while in 2014 no significant difference was observed between the two tillage practices (Table 4.5). Soil available P ranged from 3.81 to 5.26 mg kg⁻¹ in 2013 and 3.96 to 4.25 mg kg⁻¹ in 2014. The application of soil of TRP and DAP influenced significantly ($P < 0.001$) soil available P values in both years. The decreasing order of the impact of phosphorus fertilizer on soil available P was DAP > TPR Powder > TPR Pellet > Control in both seasons.

The interaction between phosphorus type and phosphorus rate of application significantly ($P < 0.001$) influenced the available phosphorus in 2013 and 2014 (Tables 4.4 and 4.5). In the first year of experimentation, for all the phosphorus types used (DAP and TPR), there was an increase in available P content with increased P application (Figure 4.3). No significant difference was observed at P0 among the different types of phosphorus applied. Diamonium phosphate applied at 11 kg ha^{-1} produced the highest P values ($P < 0.05$) when compared to the other P sources and no significant difference was observed among TPR powder, TPR pellet and the control (Figure 4.3)

At highest rate of P application (16 kg ha^{-1}), DAP plot produced significantly higher values than the TPR amendments plots and the control. Also, TPR amended plots produced significantly higher values than the control. However, no significant difference ($P > 0.05$) was observed between TPR powder and pellet form (Figure 4.3).

The result in 2014 showed no significant differences in soil available P at both P0 and P applied at 11 kg ha^{-1} among the different P types (Figure 4.4). At 16 kg P ha^{-1} , no significant difference was observed between DAP and TPR powder form (Figure 4.4). However, DAP produced significantly higher value than the pellet.

The interaction of tillage practices and phosphorus type significantly ($P < 0.002$) influenced the soil available phosphorus in both seasons (Tables 4.4 and 4.5). In the first year of experimentation, no significant difference was observed between the two tillage practices for the control plot and also, the TPR pellet (Figure 4.5). For DAP and TPR powder form, higher available P ($P < 0.05$) was recorded in CR plot than in HT plot. The values recorded under CR plot were higher when compared to HT for all the phosphorus types used (Figure 4.5). In 2014, CR plot produced higher significant value

when compared to HT only for powder form while for the other types no significant difference was observed (Figure 4.6)

The interaction between the rate of P applied and tillage practice significantly ($P < 0.01$) influenced the soil available P in both seasons. Soil available P increased as rate of P application increased under both CR and HT during the two growing seasons (Figures 4.7 and 4.8) In the first year, no significant difference was observed between the two tillage practices at both 0 and 11 kg P ha⁻¹ (Figure 4.7) while P was significantly higher under CR at 16 kg P ha⁻¹ (Figure 4.7).

In the second year, CR produced significantly higher values at P at 11 kg ha⁻¹ and 16 kg ha⁻¹. For P₀, HT plot was significantly higher in available P than CR plot (Figure 4.8). The values of P recorded under the two tillage practices in both seasons were higher than the initial value (Tables 3.2, 4.4 and 4.5).

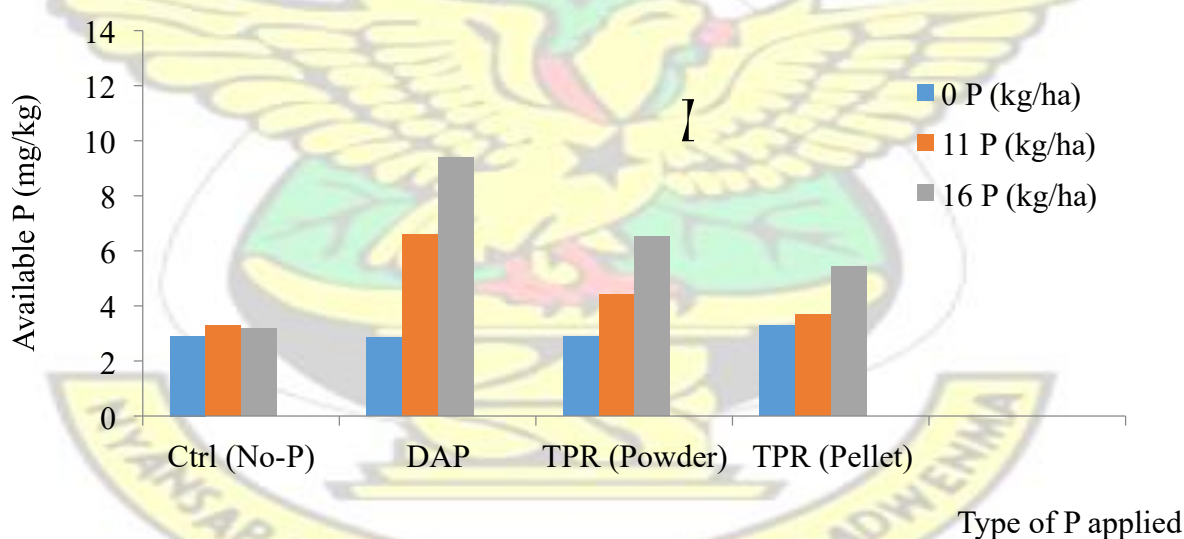


Figure 4.3: Interaction effects of phosphorus type and application rate on soil available phosphorus in 2013

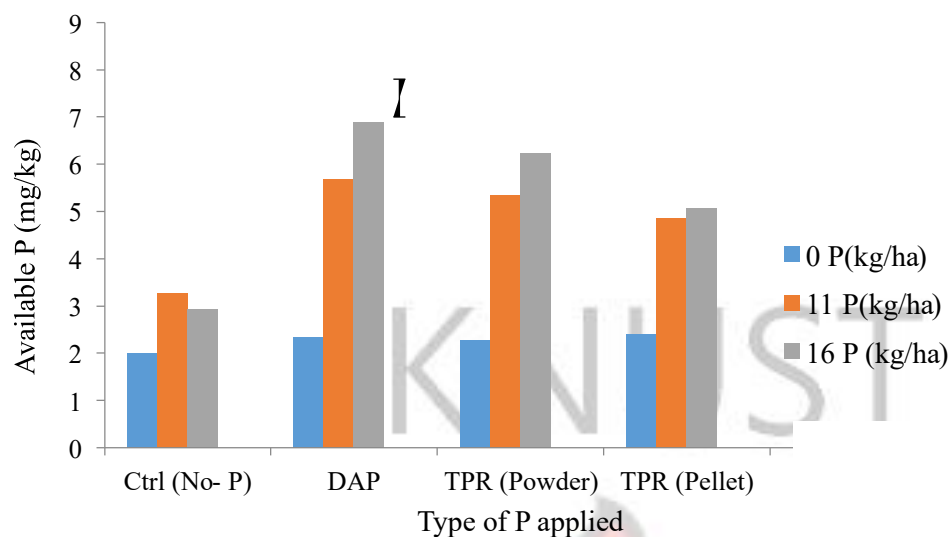


Figure 4.4: Interaction effects of phosphorus type and application rate on soil available phosphorus in 2014

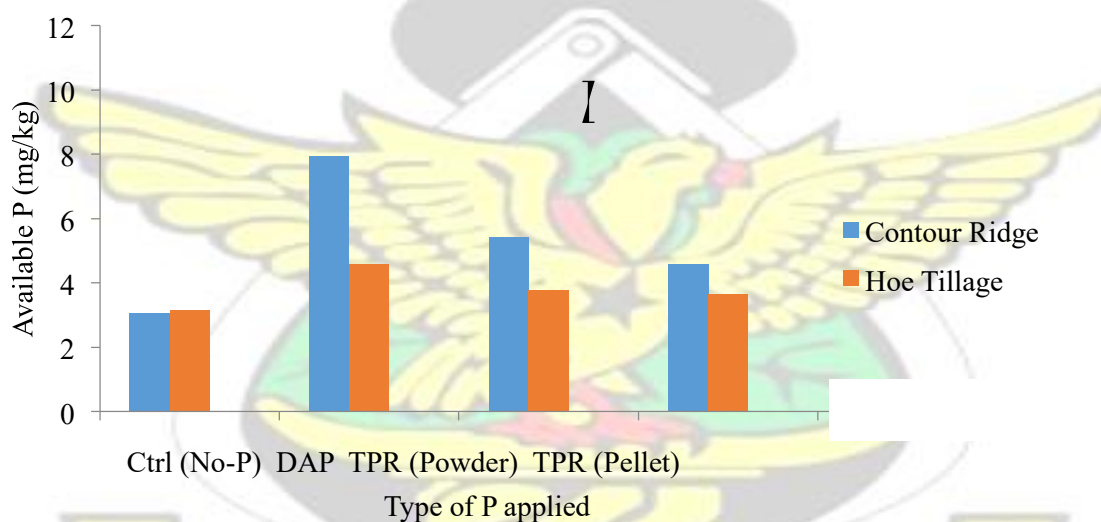


Figure 4.5: Interaction effects of tillage practices and phosphorus type on soil available phosphorus in 2013

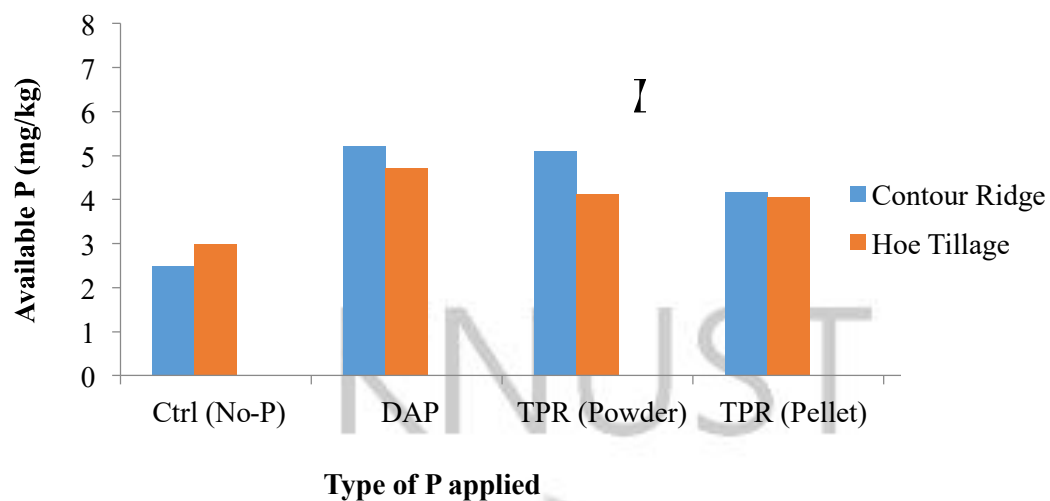


Figure 4.6: Interaction effects of tillage practices and phosphorus type on soil available phosphorus in 2014

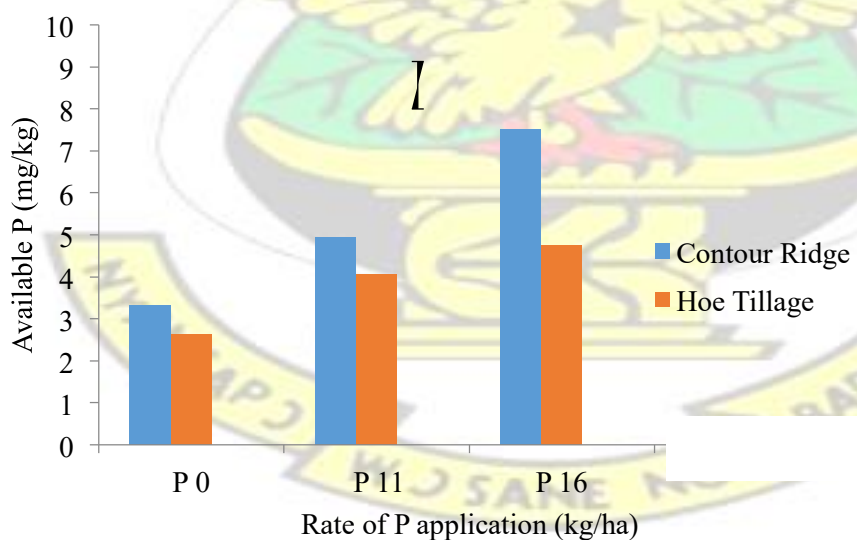


Figure 4.7 Interaction effects of tillage practices and phosphorus rate of application on soil available phosphorus in 2013

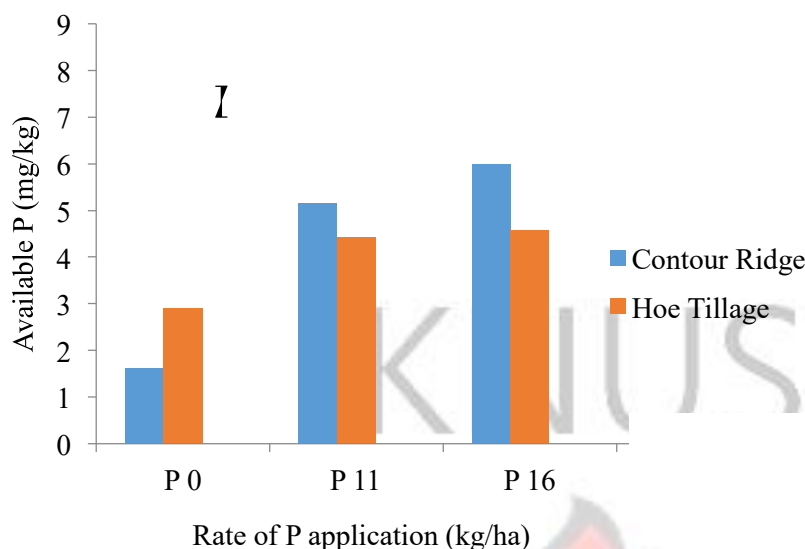


Figure 4.8 Interaction effects of tillage practices and phosphorus rate of application on soil available phosphorus in 2014

4.2.1.5 Exchangeable Ca

Soil exchangeable Ca was not significantly affected ($P > 0.05$) by the tillage practices during the two years of experimentation even though CR gave higher value than HT in both seasons (Tables 4.6 and 4.7). Application of P fertilizer significantly ($P = 0.004$) influenced soil exchangeable Ca in 2014 while in 2013 no significant differences ($P > 0.05$) were recorded among treatments. In the second year of experimentation, the exchangeable calcium values recorded in TPR amended plots was significantly higher than that of the control plot (Table 4.7). The decreasing order of the impact of P fertilizer application on soil exchangeable Ca was TPR pellet > TPR powder > DAP > control, whilst in 2013, TPR powder > TPR pellet = DAP > control (Table 4.6).

Considering the rate of P application, P applied at 11 kg ha^{-1} produced significantly higher ($P < 0.01$) exchangeable Ca when compared to P0 in 2014. However, in the first year of the experiment, no significant difference was observed among the different rates (Tables 4.6 and 4.7). The interaction between tillage practice, P type and rate of

P application did not show significant effect on soil exchangeable Ca in both seasons. The level of soil exchangeable calcium increased significantly from the first year of experimentation to the second year as shown by year analysis effect (Appendix 2a).

4.2.1.6 Exchangeable Mg

The trend of the results observed with soil exchangeable Mg was almost similar to that of exchangeable Ca. Tillage practices did not show any significant effect on soil exchangeable Mg in both seasons (Tables 4.6 and 4.7). Phosphorus application significantly ($P < 0.001$) influenced soil exchangeable Mg in 2014, with TPR amended plot producing higher value than DAP and the control plots (Table 4.7). A significant increase in exchangeable Mg was observed from 2013 to 2014 as shown by year effect analysis (Appendix 2a).

4.2.1.7 Exchangeable K

The level of soil exchangeable potassium recorded during the two years of experimentation was higher in contour ridge plot than in hoe tillage plot but the difference between the two tillage practices was not significant (Tables 4.6 and 4.7). Both the type of P fertilizer used and rate of P applied did not significantly affect ($P > 0.05$) soil exchangeable K during the two growing seasons. However, a slight increase in exchangeable K values was observed in 2014 over the initial value ($0.10 \text{ cmol}_+ \text{ kg}^{-1}$).

The interaction between the type and rate of phosphorus applied did not significantly influence soil exchangeable K in both seasons of the study. Similar result was observed for the interaction between tillage practices, P type and P rate for both seasons (Tables 4.6 and 4.7).

4.2.1.8 Exchangeable acidity

Exchangeable acidity was significantly ($P < 0.005$) influenced by tillage practices in 2013 but not in 2014. Both the types and rate of P fertilizer applied did not show any significant effect ($P > 0.05$) on soil exchangeable acidity during the two growing seasons (Tables 4.6 and 4.7). A significant ($P < 0.01$) decrease in soil exchangeable acidity was observed from 2013 to 2014 as shown by year effect analysis (Appendix 2a).

4.2.1.9 Effective cation exchange capacity

Effective cation exchange capacity was not significantly influenced by tillage practices in both seasons of the study (Tables 4.6 and 4.7). Phosphorus fertilizer application significantly ($P < 0.001$) influenced soil ECEC in 2014. The TPR plots produced higher ECEC value than the control plot (Table 4.7). No significant differences were observed between TPR powder plot and DAP while TPR pellet gave significantly higher value compared to DAP (Table 4.7).

The P application rates significantly ($P < 0.02$) influenced soil ECEC in 2014. Phosphorus applied at 11 kg ha^{-1} produced higher ECEC value than P_0 , while no significant difference was observed between P applied at 11 and 16 kg ha^{-1} (Table 4.7).

Table 4.6: Effects of soil amendments and tillage practices on soil exchangeable bases, exchangeable acidity and soil ECEC in 2013

Exch.Ca	Exch.K	Exch.Mg	Exch.ac	ECEC
----- $\text{cmol}_+ \text{ kg}^{-1}$ -----				

Tillage Practice (TP)					
CR	0.68	0.12	0.33	0.06	1.20
HT	0.59	0.07	0.29	0.04	1.00
Fpr	0.49	0.05	0.51	0.01	0.36
Phosphorus Type (PT)					
Control (No - P)	0.59	0.10	0.29	0.04	1.05
DAP	0.63	0.08	0.31	0.05	1.10
TPR (Pellet)	0.63	0.09	0.31	0.05	1.09
TPR (Powder)	0.67	0.10	0.33	0.05	1.18
Lsd (0.05)	0.13	0.02	0.06	0.01	0.21
Fpr	0.71	0.20	0.60	0.63	0.63
Phosphorus Rate (PR) kg/ha					
0	0.64	0.10	0.32	0.05	1.11
11	0.60	0.09	0.30	0.05	1.05
16	0.65	0.09	0.32	0.05	1.14
Lsd (0.05)	0.11	0.01	0.05	0.01	0.18
Fpr	0.69	0.80	0.70	0.73	0.60
Interactions					
PT x PR	0.07	0.07	0.07	0.22	0.12
TP x PT	0.90	0.43	0.90	0.28	0.88
TP x PR	0.47	0.20	0.48	0.30	0.40
TP x PT x PR	0.47	0.34	0.48	0.42	0.47
CV (%)	31.70	32.50	32.40	29.50	28.80

TP: Tillage practice PT: Phosphorus type; PR: Phosphorus rate

Table 4.7: Effects of soil amendments and tillage practices on soil exchangeable bases, exchangeable acidity and ECEC in 2014

	Exch.Ca	Exch.K	Exch.Mg	Exch.ac	ECEC
	-----cmol+ kg ⁻¹ -----				
Tillage Practice (TP)					
CR	0.80	0.12	0.36	0.04	1.41
HT	0.74	0.09	0.34	0.04	1.29
Fpr	0.32	0.06	0.38	0.28	0.15
Phosphorus Type (PT)					
Control (No-P)	0.57	0.11	0.19	0.04	0.97
DAP	0.77	0.11	0.33	0.04	1.33
TPR (Pellet)	0.92	0.10	0.47	0.04	1.62
TPR (Powder	0.84	0.11	0.41	0.04	1.48
Lsd (0.05)	0.19	0.02	0.06	0.008	0.25
Fpr	0.004	0.830	<0.001	0.49	<0.001
Phosphorus rate (PR) kg/ha					
0	0.66	0.11	0.32	0.04	1.21
11	0.92	0.11	0.39	0.04	1.53
16	0.75	0.10	0.34	0.04	1.31
Lsd (0.05)	0.16	0.014	0.06	0.007	0.22
Fpr	0.01	0.49	<0.10	0.50	0.02
Interactions					
PT x PR	0.36	0.06	0.01	0.58	0.21
TP x PT	0.38	0.29	0.08	0.27	0.24
TP x PR	0.46	0.17	0.82	0.56	0.64
TP x PR x PT	0.11	0.56	0.06	0.37	0.10
CV (%)	36.90	23.50	29.10	30.70	28.40

TP: Tillage practice PT: Phosphorus type; PR: Phosphorus rate

4.2.2 Effect of soil tillage practices on gravimetric soil water content at 0-10 and 10-20 cm depths

Tables 4.8 and 4.9 illustrate the mean soil moisture contents obtained under the two tillage practices in the 0 – 10 cm and 10 – 20 cm soil layers in both seasons. Soil gravimetric moisture content was monitored. As expected, soil moisture content increased with

increasing soil depth. Generally, higher values were observed in the contour ridge plots than the hoe tillage plots at both depths.

Table 4.8 Effect of tillage practices on gravimetric soil water content in 2013

	Gravimetric water content (%)					
	4 WAP		8 WAP		12 WAP	
	Soil depth (cm)		Soil depth (cm)		Soil depth (cm)	
	0 - 10	10 - 20	0 - 10	10 - 20	0 - 10	10 - 20
Tillage						
CR	5.23	5.90	12.18	15.51	14.67	19.52
HT	4.98	5.45	6.79	10.77	8.36	9.41
Fpr(0.05)	0.192	0.070	<0.001	<0.001	<0.001	<0.001

WAP: Week After Planting

Table 4.9 Effect of tillage practices on gravimetric soil water content in 2014

	Gravimetric water content (%)					
	4 WAP		8 WAP		12 WAP	
	Soil depth (cm)		Soil depth (cm)		Soil depth (cm)	
	0 - 10	10 - 20	0 - 10	10 - 20	0 - 10	10 - 20
Tillage						
CR	8.84	11.72	12.92	12.60	12.86	13.72
HT	8.92	11.93	12.70	12.51	10.62	13.66
Fpr(0.05)	0.80	0.40	0.80	0.90	<0.001	0.80

WAP= Week After Planting

4.2.3 Correlation between available phosphorus and some selected soil properties after harvest

Soil properties such as exchangeable calcium, exchangeable acidity, pH and soil moisture are known to impact TPR solubility when applied to soil. A weak correlation was observed between available P and different soil properties under the two soil management options in this study except for soil pH (Table 4.10). In the case of CR plot in 2013, available P was negatively correlated with SOC, exchangeable Ca and ECEC while it was positively

correlated with soil moisture and exchangeable acidity. Significant correlation was found between pH and available P in both seasons. In the second year of experimentation, a positive correlation was observed between available P and all the different soil properties and significant correlation was observed with soil

ECEC and exchangeable Ca (Table 4.10)

For HT, available P was positively correlated with the different soil properties in both seasons except for exchangeable acidity in 2014. However, significant correlation was only observed between pH and available P in the second year of experimentation.

Table: 4.10 Relationship between soil available P and some soil properties at harvest.

Soil properties	2013		2014	
	CR	HT	CR	HT
SOC	-0.27 ^{NS}	0.02 ^{NS}	0.14 ^{NS}	0.20 ^{NS}
Exch. ac	0.06 ^{NS}	0.08 ^{NS}	0.06 ^{NS}	-0.004 ^{NS}
Exch. Ca	-0.14 ^{NS}	0.01 ^{NS}	0.34 ^S	0.24 ^{NS}
ECEC	-0.14 ^{NS}	0.02 ^{NS}	0.41 ^S	0.25 ^{NS}
pH	0.33 [*]	0.28 ^{NS}	0.69 ^{***}	0.68 ^{***}
Soil moisture	0.14 ^{NS}	0.11 ^{NS}	0.22 ^{NS}	0.06 ^{NS}

NS: not significant, * significant at $P < 0.05$, ** significant at $P < 0.01$, *** significant at $P < 0.001$ - SOC: Soil organic carbon; Exch.ac: Exchangeable acidity; Exch.Ca: Exchangeable Ca.

Multiple regression function describing the relationship between available P and the soil properties are shown in Tables 4.11 and 4.12. For CR plot, available P was not significantly ($P > 0.05$) influenced by soil properties except for pH in both seasons and SOC in 2013 (Table 4.11). Similarly, only soil pH significantly influenced soil available P for HT plot in 2014.

Table 4.11: Multiple regression of soil available P with soil properties at harvest in 2013

Soil property	CR			HT		
	Coeff	SE	Significance	Coeff	SE	Significance
Constant	-8.35	7.76	0.29	-2.54	4.25	0.55
SOC	-9.32	4.49	0.04	-0.51	3.65	0.88
Exch. ac	20.60	38.30	0.60	4.80	21.40	0.82
Exch. Ca	7.60	15.60	0.63	-3.30	12.40	0.79
ECEC	-5.50	10.20	0.59	1.81	7.58	0.81
pH	3.13	1.28	0.02	1.42	1.00	0.17
Moisture	0.21	0.26	0.43	0.05	0.14	0.73

Coeff: Coefficient; SE: standard error;

$Y_{CR} = 3.13 (\pm 1.28) \text{ pH} - 9.32 (\pm 4.49) \text{ SOC}$ $P < 0.05$; $R^2 = 0.30$

HT ($P > 0.05$) $R^2 = 10$

Table 4.12: Multiple regression of soil available P with soil properties at harvest in 2014

Soil property	CR			HT		
	Coeff	SE	Significance	Coeff	SE	Significance
Constant	-10.94	2.95	< 0.001	-4.48	2.15	0.05
SOC	-1.10	2.88	0.70	-0.63	1.23	0.61
Exch. ac	18.10	18.8	0.34	6.30	21.30	0.77
Exch. Ca	-1.20	7.39	0.87	-2.23	3.47	0.52
ECEC	2.38	5.15	0.64	1.25	2.27	0.58
pH	2.49	0.61	< 0.001	1.85	0.40	< 0.001
Moisture	0.03	0.15	0.85	-0.03	0.11	0.78

Coeff: coefficient; SE: Standard error;

$Y_{CR} = -10.94 (\pm 2.95) + 2.49 (\pm 0.61) \text{ pH}$ $P < 0.001$; $R^2 = 0.44$

$Y_{HT} = -4.48 (\pm 2.15) + 1.85 (\pm 0.40) \text{ pH}$ $P < 0.003$; $R^2 = 0.37$

4.2.4: Effects of tillage practices and soil amendments on maize growth and yield

4.2.4.1 Maize grain yield

The effects of tillage practices and soil amendment on maize grain and biomass yields are shown in Table 4.13. Tillage practice did not affect significantly ($P > 0.05$) maize grain yield in both cropping seasons, though higher values were recorded under CR plot than on HT plot. Yield values ranged from 1267 to 1544 kg ha⁻¹ in 2013 and 1299 to 1509 kg ha⁻¹ in 2014 under HT and CR (Table 4.13). The increase in grain yield under CR over the HT was 22 % and 16 %, respectively in 2013 and 2014. The application of phosphorus significantly ($P < 0.001$) influenced the maize grain yield in the decreasing order of DAP > TPR powder form > TPR pellet form > control in both seasons.

The interaction between phosphorus type and rate of application significantly influenced ($P < 0.001$) maize grain yield in both seasons (Table 4.13). A general increase in maize grain yield was observed in phosphorus amended plots from low rate of P application to higher rate in both seasons (Figures 4.9 and 4.10). At P0, no significant difference was observed between the different types of phosphorus used and the control in 2014 (Figure 4.10), while TPR in pellet recorded significantly higher value than the control in 2013 (Figure 4.9). Significant difference was observed at 11 and 16 kg P ha⁻¹ between DAP and the TPR forms in both seasons (Figures 4.9 and 4.10). Tilemsi phosphate rock in powder form produced significantly higher grain yield than TPR in pellet form and control at both 11 and 16 kg ha⁻¹ during the two growing seasons (Figures 4.9 and 4.10). No significant difference ($P > 0.05$) in grain yield was observed between TPR pellet and the control at 11 kg P ha⁻¹, in the first year (Figure 4.9) while in the second year TPR pellet produced significantly higher values than the control (Figure 4.10). Tilemsi phosphate rock pellet

form produced significantly ($P < 0.05$) higher grain yield at P applied at 16 kg ha⁻¹ than the control in both seasons (Figures 4.9 and 4.10).

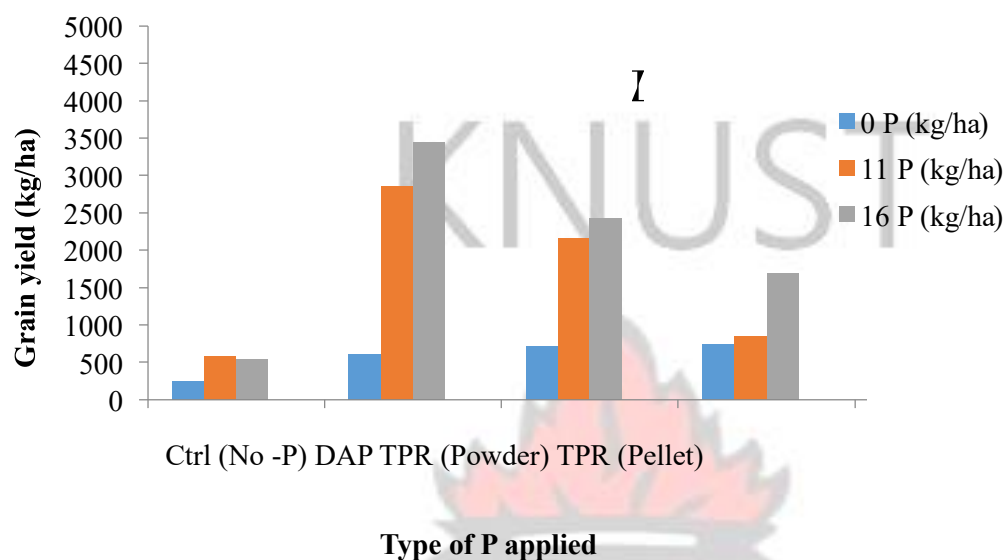


Figure 4.9: Interaction effects of phosphorus type and rate of application on maize grain yield in 2013

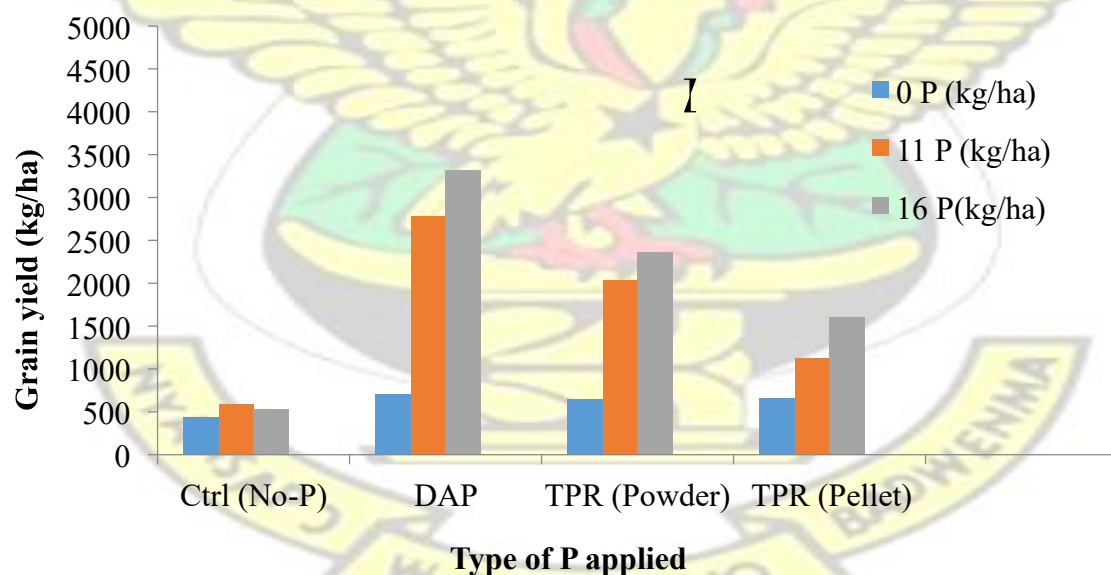


Figure 4.10: Interaction effects of phosphorus type and rate of application on maize grain yield in 2014

4.2.4.2 Effects of tillage practices and soil amendments on maize biomass yield

Maize biomass yield was not significantly affected by tillage in both seasons (Table 4.13).

However, the contour ridge produced higher biomass yield than hoe tillage during the two growing seasons. The percentage yield differences were 32 % and 14 %, respectively in 2013 and 2014 (Table 4.13). Among the different types of P applied in 2013, phosphorus applied as DAP produced higher biomass yield than TPR applied as pellet and also, the control. No significant difference was observed between DAP and TPR applied in powder form (Table 4.13). The same trend was observed in 2014 (Table 4.13).

Considering the rate of phosphorus application in 2013, phosphorus applied at 16 kg ha⁻¹ and 11 kg ha⁻¹ as TPR (powder and pellet) and DAP produced significantly ($P < 0.001$) higher biomass than P0. No significant difference was observed between phosphorus applied at 11 and 16 kg ha⁻¹. In 2014, P applied at 16 kg ha⁻¹ produced higher biomass yield ($P < 0.05$) than P applied at both 0 and 11 kg ha⁻¹. In 2014, the interaction of tillage practice and phosphorus sources significantly ($P < 0.02$) influenced maize biomass yield (Table 4.13). Under CR plot, DAP produced significantly higher biomass yield than HT, while no significant difference was observed with the other phosphorus sources such as TPR pellet and TPR in powder form (Figure 4.11)

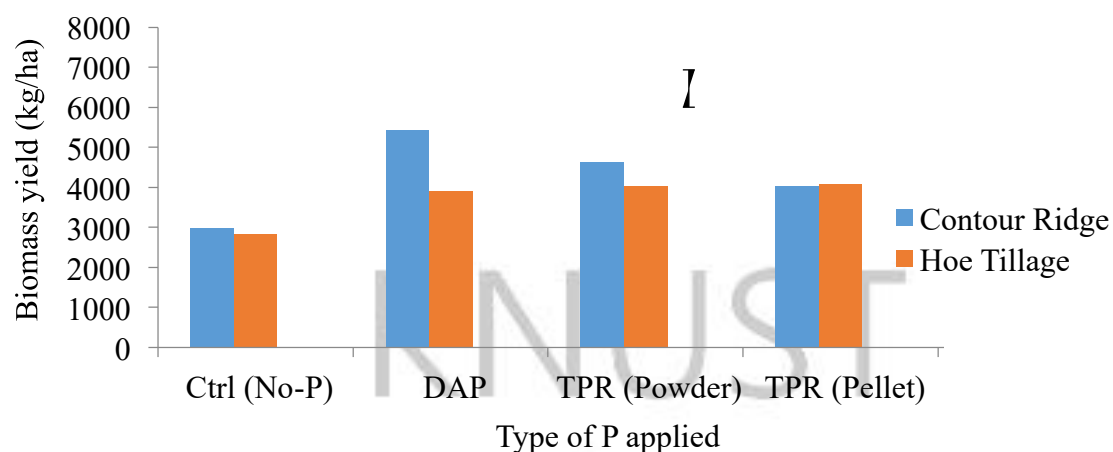


Figure 4.11: Interaction effects of tillage practices and phosphorus type on maize biomass yield in 2014

Table 4.13: Effects of soil amendments and tillage practices on maize grain and biomass yields

	2013		2014	
	Grain	Biomass	Grain	Biomass
	(kg ha ⁻¹)			
Tillage Practice (TP)				
CR	1544	4391	1504	4261
HT	1267	3321	1299	3727
Fpr	0.07	0.11	0.08	0.14
Phosphorus Type (PT)				
Control (No- P)	460	2753	521	2909
DAP	2300	4790	2270	4667
TPR (Pellet)	1097	3494	1133	4073
TPR (Powder)	1765	4389	1683	4326
Lsd (0.05)	228.50	838.40	219.20	535.10
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Phosphorus Rate (PR)				
0	578	2729	615	2871
11	1610	4146	1633	4298
16	2029	4694	1957	4812
Lsd (0.05)	197.90	726.10	189.80	463.40
FPr	< 0.001	< 0.001	< 0.001	< 0.001
Interactions				
PT x PR	< 0.001	0.60	< 0.001	0.001
TP x PT	0.39	0.05	0.17	0.02
TP x PR	0.64	0.38	0.80	0.27
TP x PR x PT	0.82	0.45	0.32	0.65
CV (%)	24.20	32.40	23.30	19.90

4.2.5 Correlation between maize yield and some selected soil properties

Table 4.14 shows the relationship between grain yield and some chemical properties of the soil under the two tillage practices. Soil available P significantly correlated positively with grain yield in both seasons and for the two tillage practices. Similarly, soil pH significantly correlated positively with grain yield under CR in both seasons, whereas for HT in 2014, pH was significantly correlated positively with grain yield but not in 2013 (Table 4.14). Total N significantly correlated positively with grain yield in 2014 under both CR and HT. Soil exchangeable Mg significantly correlated positively to grain yield in 2014 in CR plot. Conversely, no significant correlation was observed with soil moisture, SOC, exchangeable acidity, exchangeable Ca and K with grain yield during the two growing seasons under both CR and HT practices (Table 4.14).

Table 4.14: Relationship between some selected soil properties and maize grain yield at harvest

Soils properties	2013		2014	
	CR	HT	CR	HT
Av. P	0.84 ^{***}	0.61 ^{***}	0.87 ^{**}	0.74 ^{**}
% moisture	0.21 ^{NS}	-0.02 ^{NS}	0.20 ^{NS}	0.15 ^{NS}
Exch .ac	0.21 ^{NS}	-0.09 ^{NS}	0.07 ^{NS}	0.06 ^{NS}
Exch Ca	-0.08 ^{NS}	0.17 ^{NS}	0.27 ^{NS}	0.23 ^{NS}
pH	0.38 [*]	0.29 ^{NS}	0.64 ^{**}	0.48 [*]
Exch K	-0.31 ^{NS}	0.13 ^{NS}	-0.10 ^{NS}	-0.07 ^{NS}
Exch Mg	-0.09 ^{NS}	0.16 ^{NS}	0.40 [*]	0.28 ^{NS}
Total N	-0.13 ^{NS}	-0.05 ^{NS}	0.55 ^{**}	0.67 ^{**}
SOC	-0.19 ^{NS}	-0.04 ^{NS}	0.19 ^{NS}	0.19 ^{NS}

Exch.ac: Exchangeable acidity, TN: Total nitrogen NS: not significant, *: significant at $P < 0.05$, ** significant at $P < 0.01$, *** significant at $P < 0.001$

A multiple regression function showing the relationship between grain yield and some selected soil properties are presented in Tables 4.15 and 4.16. The grain yield under CR plot was not significantly ($P > 0.05$) influenced by different soil properties except soil available P and pH. The analysis showed that soil available P significantly ($P < 0.001$) increased grain yield in both seasons (Table 4.15). Furthermore, soil available P for HT plot significantly ($P < 0.01$) increased grain yield in both seasons (Table 4.16). Conversely, the other soil properties had no significant ($P > 0.05$) influence on the grain yield, except for total N in 2014.

Table 4.15: Multiple regression of grain yield with soil properties in 2013

Soil properties	CR			HT		
	Coeff	SE	Significance	Coeff	SE	Significance
Constant	-2830	1614	0.09	-2135	2199	0.34
Av. P	267.20	38.8	< 0.001	3516	91.8	< 0.001
Moisture	24.60	53.30	0.64	0.7	80.6	0.99
Exch. Ac	15350	7698	0.06	-14699	10479	0.17
Exch. Ca	4589	9369	0.62	1763	14937	0.24
Exch. K	-5146	3157	0.11	-2837	5055	0.57
Exch. Mg	-8467	18489	0.65	-32894	29515	0.27
Total N	893	16489	0.95	-2598	34693	0.94
SOC	-533	973	0.58	-2149	1820	0.24
pH	515	282	0.05	643	543	0.24

Coeff: coefficient; SE: standard error.

$$Y_{CR} = 267.20 (\pm 38.8) \text{ Av.P} + 515 (\pm 282) \text{ pH} \quad P < 0.001 \quad R^2 = 0.74$$

$$Y_{HT} = 3516 (\pm 91.8) \text{ Av.P} \quad P < 0.01 \quad R^2 = 0.42$$

Table 4.16: Multiple regression of grain yield with soil properties in 2014

HT						
CR				HT		
Soil property	Coeff	S E	Significance	Coeff	SE	Significance
Constant	-451	1349	0.74	-2022	1768	0.26
Av. P	343.30	61.2	< 0.001	429	157	0.01
Moisture	-15	51.4	0.77	108.9	83.3	0.20
Exch. Ac	873	6668	0.89	10048	15402	0.52
Exch. Ca	-449	794	0.57	483	1140	0.67
Exch. K	-486	4018	0.90	-248	5869	0.96
Exch.Mg	826	1702	0.63	-650	2159	0.76
Total N	220	251	0.38	467	222	0.04
SOC	187	969	0.84	259	874	0.76
pH	35	258	0.89	-266	376	0.48

Coeff: coefficient, SE: standard error

$Y_{CR} = 343.30 (\pm 61.2) \text{ Av.P}$

$P < 0.001 \quad R^2 = 0.69$

$Y_{HT} = 429 (\pm 157) \text{ Av.P} + 467 (\pm 222) \text{ Total N}$

$P < 0.001 ; R^2 = 0.52$

4.2.6 Effects of soil tillage practices and soil amendments on N and P uptake by

maize grain and biomass

4.2.6.1 Phosphorus uptake by maize grain

Tillage practice significantly ($P < 0.005$) influenced grain P uptake in both seasons (Table 4.17). Higher P uptake by grain was observed in contour ridge plot than in hoe tillage plot during the two growing seasons (Table 4.17). The increase in P uptake by grain in CR over the HT was 44 % and 65 % respectively in 2013 and 2014. The P uptake by grain values increased from the first year to the second year of experiment as shown by year effect analysis (Appendix 2b).

In the first year of experimentation, the interaction of tillage and phosphorus types significantly ($P < 0.001$) influenced the P uptake by grain. Contour ridge plot produced significantly higher value with DAP and TPR powder amended plots (Figure 4.12), while for the control and TPR pellet no significant difference was observed between the two tillage practices (Figure 4.12).

Considering the interaction of tillage practice and phosphorus rate of application, it was observed that P uptake by grain increased with increasing P application rates in both CR and HT plots (Figure 4.13). However, no significant difference was observed between the two tillage systems at P0 (Figure 4.13) but significantly higher P uptake by grain was recorded under CR at 11 and 16 kg ha⁻¹. In the second year, as observed in 2013, the interaction of tillage practice and phosphorus type significantly ($P < 0.001$) influenced maize grain P uptake (Table 4.17). Contour ridge plot produced significantly higher values with DAP and TRP powder form when compared to HT while for the control plot and TPR pellet, no significant difference was observed between the two tillages practices (Figure 4.14)

The interaction of tillage practice and phosphorus rates significantly affected the maize grain P uptake (Table 4.17). A general increase in grain P uptake with increased P application was observed under the two tillages practices (Figure 4.15). CR plot produced significantly higher values with P applied at 11 and 16 kg ha⁻¹ compared to HT plot while at P0, no significant difference was observed between the two tillages practices (Figure 4.15).

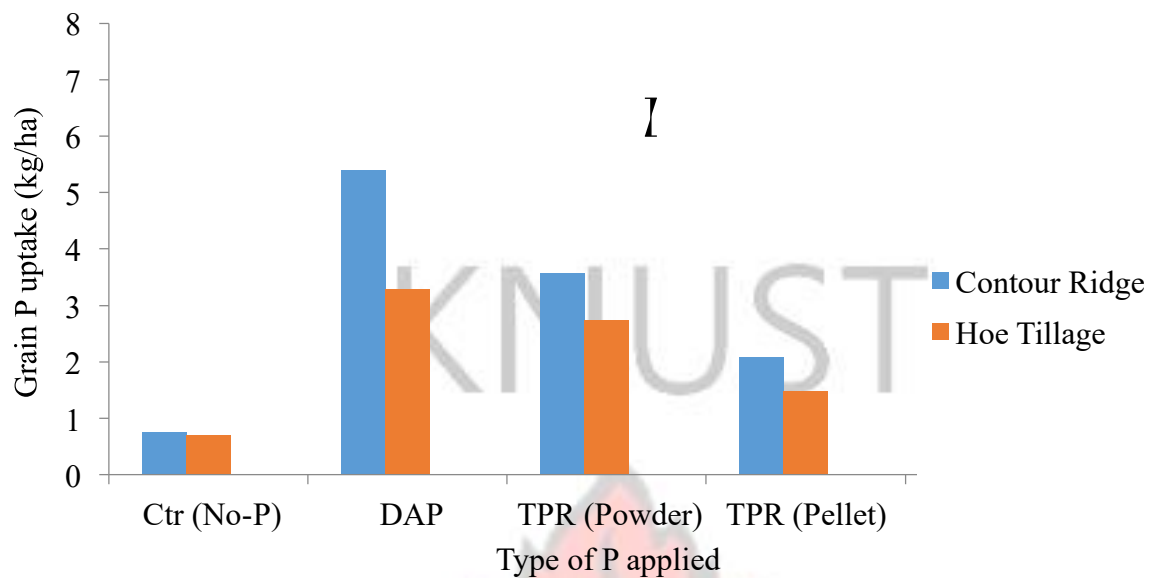


Figure 4.12: Interaction effects of tillage practices and phosphorus type on P uptake by maize grain in 2013

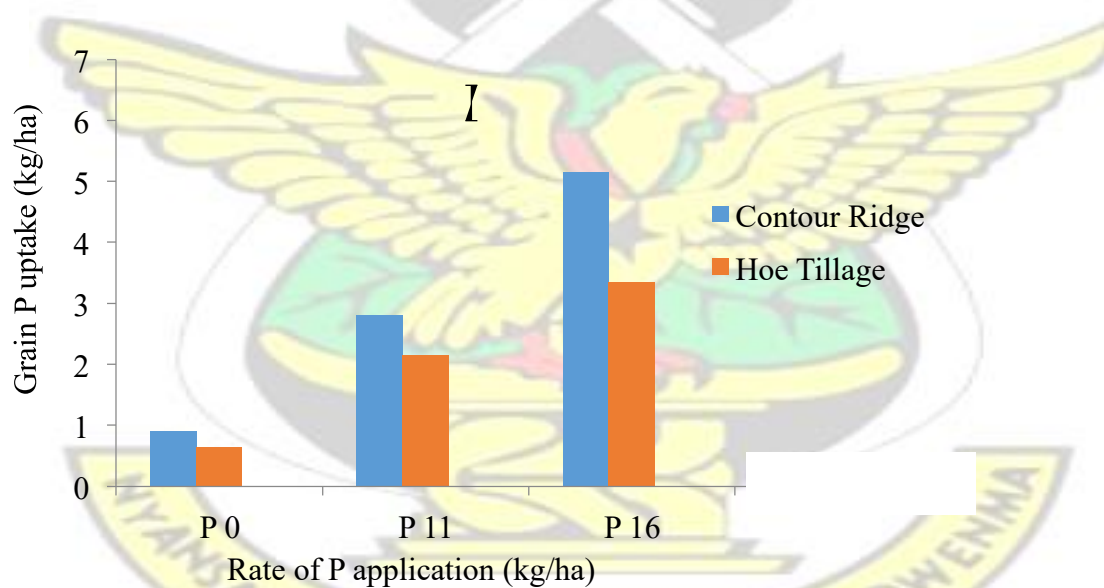


Figure 4.13: Interaction effects of tillage practices and phosphorus rate of application on P uptake by maize grain in 2013

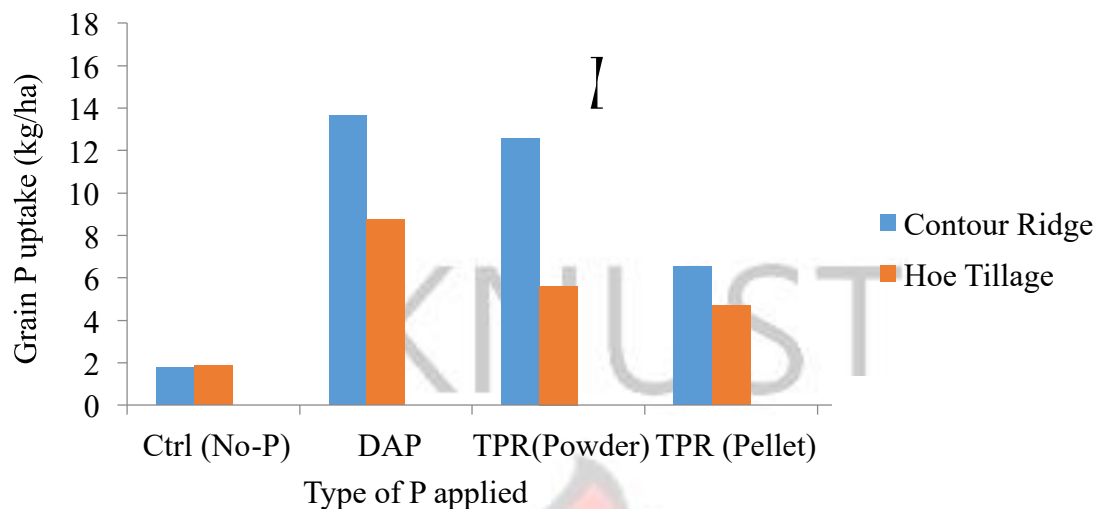


Figure 4.14: Interaction effects of tillage practices and phosphorus type on P uptake by maize grain in 2014

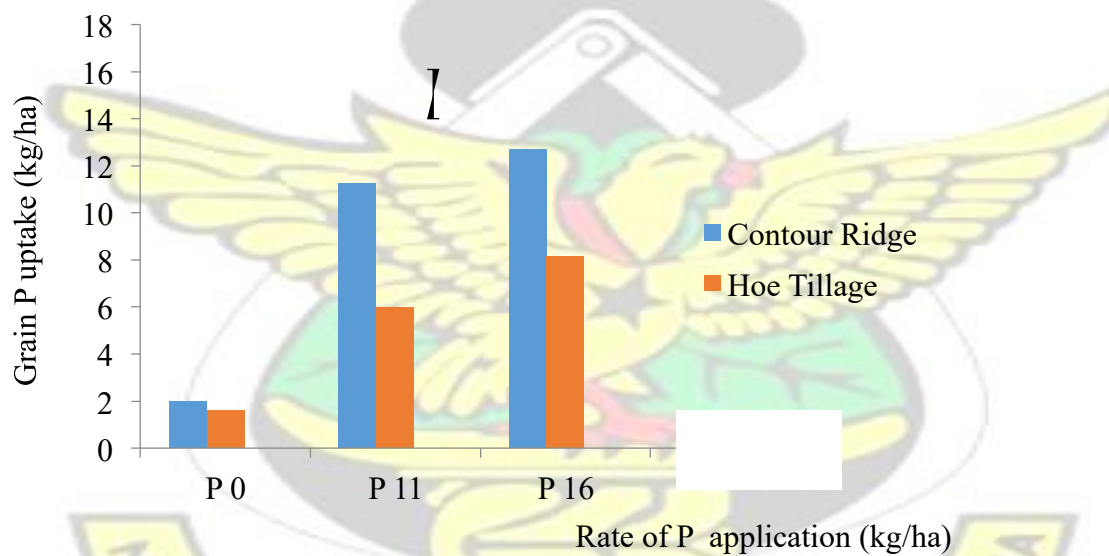


Figure 4.15: Interaction effects of tillage practices and phosphorus rate of application on maize grain P uptake in 2014

4.2.6.2 Phosphorus uptake in maize biomass

The two tillage options were not significantly different in P uptake by maize biomass during the two growing seasons (Table 4.17). Like grain uptake, biomass P uptake was higher under CR than under HT. The increase in biomass P uptake for CR over HT was 29 % and 21 %, respectively in 2013 and 2014.

Type of phosphorus (DAP and TPR) applied significantly ($P < 0.001$) influenced P uptake by maize biomass in both seasons (Table 4.17). Phosphorus amended plots produced significantly higher values than the control plot. Among the types of phosphorus fertilizer applied, DAP produced significantly higher values relative to TPR pellet form while no significant difference was observed between DAP and TPR powder form (Table 4.17). In 2014, significant difference was observed between phosphorus amended plots and the control, while no significant difference was observed among the P amended plots. The decreasing order of the impact of phosphorus application on maize biomass P uptake was DAP > TPR powder form > TPR pellet form > control in both seasons.

Increasing the rate of P applied significantly ($P < 0.001$) increased the biomass P uptake (Table 4.17). Significant difference was observed between P applied at 16 kg ha⁻¹ compared to 0 and 11 kg ha⁻¹ P.

The interaction between tillage practice and phosphorus type significantly influenced maize biomass P uptake in 2014. CR plot produced significantly higher biomass P uptake values with DAP amendment when compared to HT, while no significant difference was observed among the other phosphorus types (Figure 4.16).

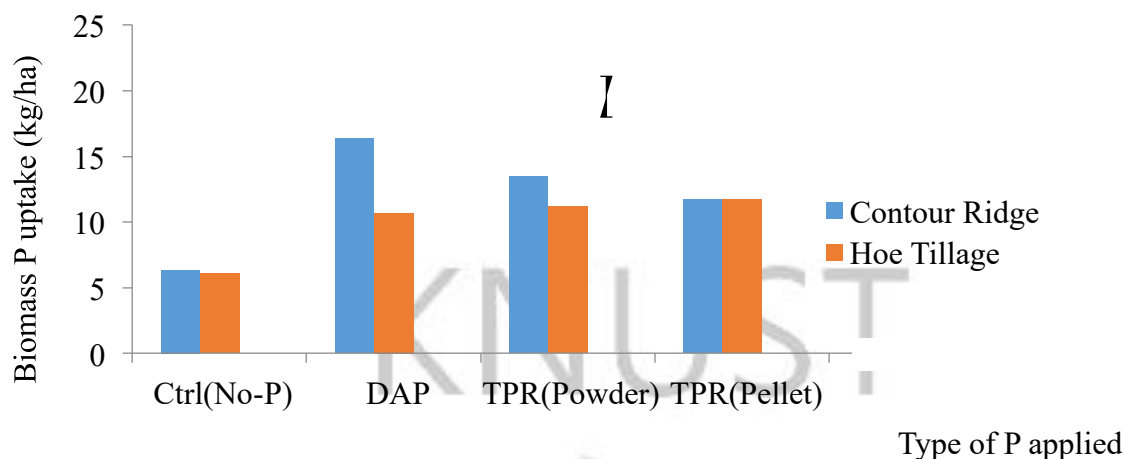


Figure 4.16: Interaction effects of tillage practices and phosphorus type on P uptake by maize biomass in 2014

Table : 4.17 Effects of tillage practices and soil amendments on phosphorus uptake by maize grain and biomass

	2013		2014	
	Grain	Biomass	Grain	Biomass
	----- (kg ha ⁻¹) -----			
Tillage Practice (TP)				
CR	2.95	5.25	8.64	11.97
HT	2.05	4.06	5.24	9.92
Fpr	0.01	0.14	0.01	0.10
Phosphorus Type (PT)				
Control (No-P)	0.72	2.66	1.82	6.23
DAP	4.34	6.10	11.21	13.52
TPR (Pellet)	1.78	4.31	5.63	11.72
TPR (Powder)	3.16	5.54	9.10	12.32
Lsd (0.05)	0.48	1.10	1.66	1.82
Fpr	<0.001	<0.001	<0.001	<0.001
Phosphorus rate (PR) kg/ha				
0	0.77	2.96	1.80	6.22
11	2.48	4.70	8.60	12.32
16	4.25	6.29	10.41	14.29
Lsd (0.05)	0.41	0.95	1.43	1.57
Fpr	<0.001	<0.001	<0.001	<0.001
Interactions				
PT x PR	<0.001	0.32	<0.001	<0.001

TP x PT	<0.001	0.11	<0.001	0.01
TP x PR	0.002	0.57	0.003	0.34
TP x PT x PR	0.004	0.35	0.09	0.68
CV (%)	28.80	35.30	35.60	24.80

4.2.6.3 Effects of tillage practices and soil amendments on nitrogen uptake in

maize grain

Tillage practices significantly ($P < 0.05$) influenced grain N uptake in 2013, while in 2014 no significant difference was observed between the two tillage practices (Table 4.18). The values of grain N uptake ranged from 22.41 to 16.45 kg ha⁻¹, respectively under CR and HT in 2013, and 24.72 to 27.12 kg ha⁻¹, respectively under CR and HT in 2014.

The interaction of phosphorus type and phosphorus rate of application significantly influenced ($P < 0.01$) grain nitrogen uptake in both seasons (Table 4.18). In 2013, the maize grain N uptake generally increased as P application rate increased (Figure 4.17).

When P was applied at 11 and 16 kg ha⁻¹ significant differences were observed among DAP and the other P sources. A similar trend was observed for TPR powder compared to TPR pellet and the control (Figure 4.17). Similar results were observed in 2014 (Figure 4.18). However, no significant difference was observed between TPR pellet form and the control for P applied at 11 kg ha⁻¹. Tilemsi phosphate rock pellet form produced higher grain N value for P applied at 16 kg ha⁻¹ compared to the control (Figure 4.17). In 2014, both P applied at 11 and 16 kg ha⁻¹ TPR pellet form gave higher value than the control (Figure 4.18).

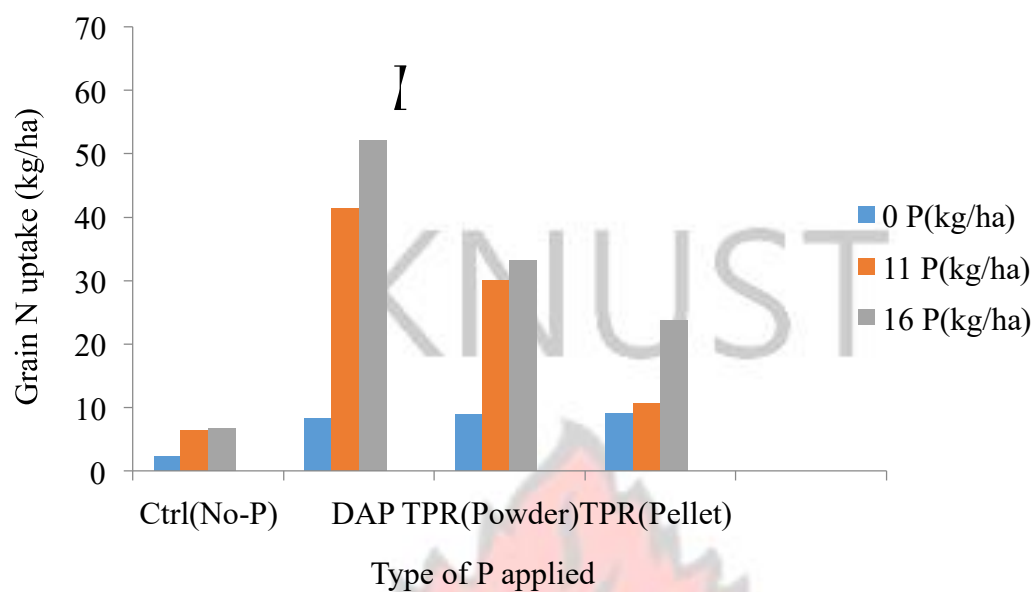


Figure 4.17 Interaction effects of phosphorus type and rate of application on nitrogen uptake by maize grain in 2013

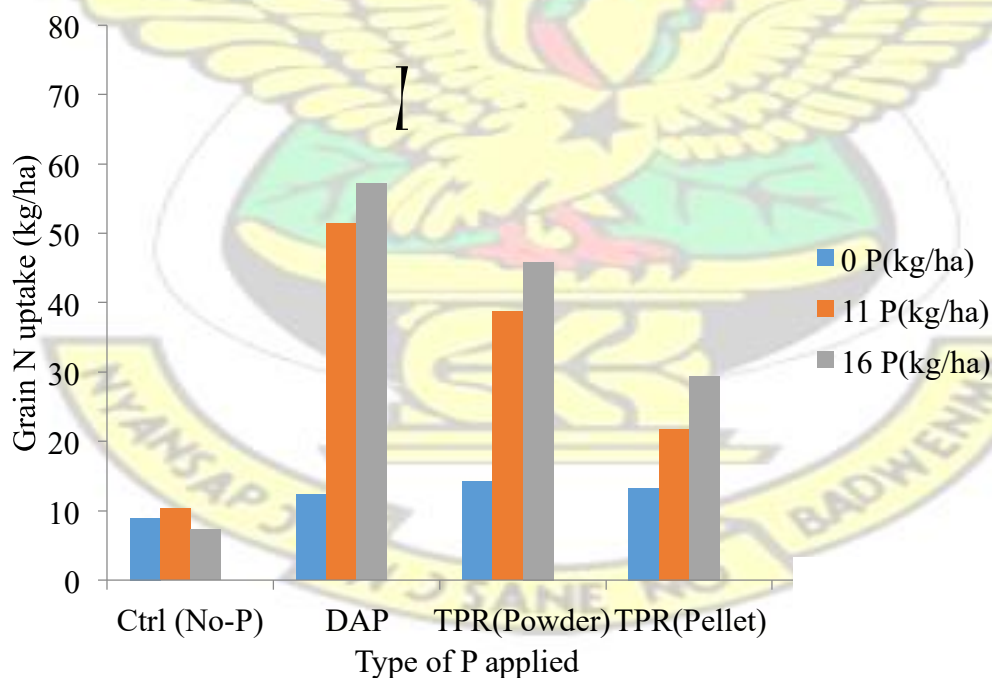


Figure 4.18 Interaction effects of phosphorus type and rate of application on nitrogen uptake by maize grain in 2014

4.2.6.4 Nitrogen uptake in maize biomass

Tillage practices did not have any significant impact on N uptake by maize biomass in both cropping seasons (Table 4.18). The value observed on CR plot was however higher than that of HT plot in both cropping seasons.

Application of P fertilizer significantly ($P < 0.001$) affected biomass N uptake during the two years of study (Table 4.18). DAP amended plot gave significantly higher ($P < 0.001$) value than TPR plot and the control. Also TPR amended plots gave significantly higher N biomass uptake than the control in 2013. In 2014, application of different types of phosphorus significantly ($P < 0.001$) produced higher biomass N uptake compared to the control (Table 4.18). The decreasing order of the impact of phosphorus type on maize biomass uptake was $\text{DAP} > \text{TPR pellet form} > \text{TPR powder form} > \text{Control}$. In 2014, biomass N uptake decreased in the order: $\text{DAP} > \text{TPR powder form} > \text{TPR pellet form} > \text{Control}$.

Considering the phosphorus application rates, significant ($P < 0.001$) difference was observed in biomass N uptake between phosphorus applied at 11 and 16 kg ha⁻¹ compared to P₀. However, no significant difference was observed between the two rates (11 and 16 kg ha⁻¹) in both seasons (Table 4.18)

The interaction between tillage practice and phosphorus type significantly ($P < 0.001$) influenced biomass N uptake in 2013 (Table 4.18). CR enabled higher N biomass uptake with DAP while no significant difference was observed between the two tillage practices for TPR amended plot (Figure 4.19).

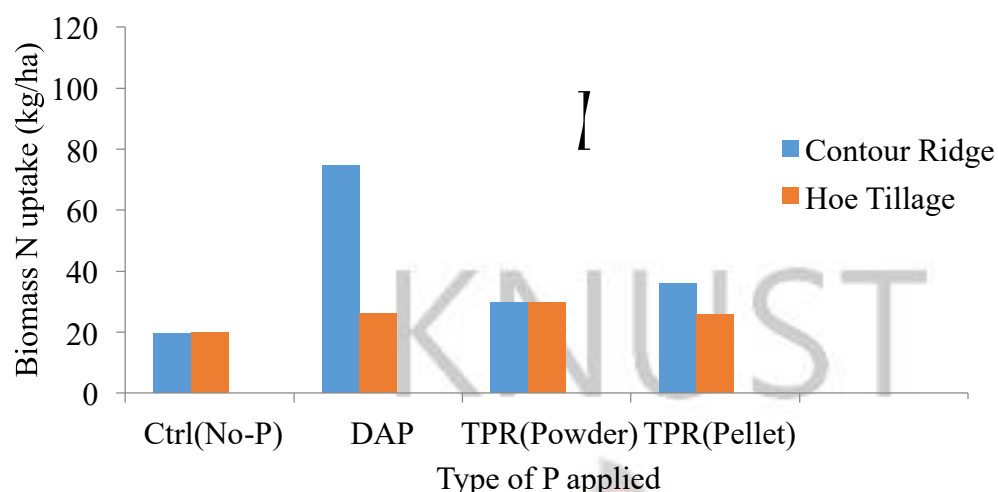


Figure 4.19: Interaction effects of tillage practices and phosphorus type on N uptake by maize biomass in 2013

Table 4.18 Effects of tillage practices and soil amendments on nitrogen uptake by the grain and biomass

	2013		2014	
	Grain	Biomass	------(kg ha ⁻¹)--	
Tillage Practice (TP)				
CR	22.41	40.0	24.72	69.70
HT	16.45	25.50	27.12	50.80
Fpr	0.03	0.08	0.41	0.10
Phosphorus Type (PT)				
Control (No-P)	5.15	19.80	8.88	32.90
DAP	33.95	50.60	40.33	75.49
TPR (Pellet)	14.53	30.90	21.49	62.12
TPR (Powder	24.09	29.70	32.96	70.44
Lsd (0.05)	3.94	9.74	5.19	17.96
Fpr	<0.001	<0.001	<0.001	<0.001
Phosphorus Rate (PR)kg/ha				
0	7.22	21.60	12.21	41.10
11	22.15	37.20	30.57	75.30
16	28.92	39.40	34.96	64.30
Lsd (0.05)	3.41	8.44	4.50	15.55
Fpr	<0.001	<0.001	<0.001	<0.001
Interactions				

PT x PR	<0.001	0.43	<0.001	0.80
TP x PT	0.09	<0.001	0.14	0.14
TP x PR	0.40	0.32	0.66	0.22
TP x PT x PR	0.89	0.60	0.35	0.36
CV (%)	30.20	44.30	29.80	44.40

4.2.7 Effects of tillage practices and soil amendments on phosphorus use

efficiency

4.2.7.1 Relative agronomic effectiveness as affected by tillage practices

The results of relative agronomic effectiveness (RAE) of Tilemsi phosphate rock (TPR) under contour ridge and hoe tillage during the two cropping years are shown in Tables 4.19 and 4.20.

On contour ridge plot, the values of RAE recorded for P applied at 11 kg P ha⁻¹ were 31 % and 78 %, respectively for pellet and powder form in 2013. While in 2014, RAE at 11 kg P ha⁻¹ were 32 % to 88 %, respectively for pellet and powder form of TPR. The RAE at 16 kg P ha⁻¹ were 44 % and 64 % in 2013, and 39 % and 65 %, respectively in 2014 for pellet and powder forms of TPR (Table 4.19).

On hoe tillage plot, RAE at 11 kg P ha⁻¹ were 15 % and 69 % in 2013, and in the second year of experimentation the values were 30 % and 50 % for TPR pellet and powder forms, respectively. In 2013, RAE values at 16 kg P ha⁻¹ were 48 % and 73 %, while in 2014, 45 % and 71 % were obtained respectively for pellet and powder forms (Table 4.20).

Relative agronomic effectiveness decreased with increased fertilizer application rate for TPR applied in the powder form on CR plot. In contrast to pellet form of TPR, RAE increased with increasing P application rate. A similar trend was observed in 2014 (Table 4.19). For HT plot, it was observed that RAE increased as P application rate increased for both pellet and powder forms of TPR (Table 4.20)

Table 4.19: Maize grain yield and relative agronomic effectiveness of TPR and DAP on CR plot

	2013				2014			
	P rates (kg/ha)				P rates (kg/ha)			
	P11		P16		P11		P16	
	Yield	RAE	Yield	RAE	Yield	RAE	Yield	RAE
Amendments	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)
Pellet	1114	31	1810	44	1159	32	1635	39
Powder	2405	78	2543	64	2508	88	2470	65
DAP	3016	100	3802	100	2786	100	3619	100
Control-P0	221.42	-	221.42	-	380.95	-	380.95	-

RAE: Relative agronomic effectiveness P11: P applied at 11 kg/ha; P16: P applied at 16 kg/ha

Table 4.20: Maize grain yield and relative agronomic effectiveness of TRP compared to DAP on HT plot

	2013				2014			
	P rates (kg/ha)				P rates (kg/ha)			
	P11		P16		P11		P16	
	Yield	RAE	Yield	RAE	Yield	RAE	Yield	RAE
Amendments	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)
Pellet	586	15	1583	48	1095	30	1581	45
Powder	1910	69	2319	73	1556	50	2262	71
DAP	2685	100	3079	100	2778	100	3032	100
Control-P0	221.42	-	221.42	-	380.95	-	380.95	-

RAE: Relative agronomic effectiveness; P11: P applied at 11 kg/ha; P16: applied at 16 kg/ha

4.2.7.2 Effects of tillage practices and soil amendments on phosphorus agronomic efficiency (PAE), partial factor productivity (PFP) and recovery efficiency

(PRE)

Tillage practice significantly ($P < 0.01$) influenced PRE in both 2013 and 2014 (Table 4.21).

In both years, PRE was higher under CR than HT.

Soil amendments significantly ($P < 0.001$) influenced phosphorus efficiency indices in both years (Table 4.21). DAP amended plot gave significantly ($P < 0.001$) higher values compared to TPR amended plot. In all cases, plots amended with TPR in powder form produced higher values than TPR in pellet form. Phosphorus agronomic efficiency, PFP and PRE among the amendments decreased in the order $\text{DAP} > \text{TPR powder} > \text{TPR pellet}$.

In the first year of the study, it was observed that, PAE and PFP decreased as P application rate increased when P was applied as DAP and TPR powder form, while the reverse trend was observed with TPR pellet form (Figures 4.20 and 4.21). Phosphorus recovery efficiency, however, increased with increase in P application rate for DAP treated plots as well as TPR amended plots (Figure 4.22)

In the second year of the study, the PFP and PRE decreased as P application rate increased when P was applied as DAP and TPR in powder and pellet form on CR plot (Figures 4.24 and 4.25). The reverse trend was observed with TPR pellet form with PAE (Figure 4.23). On HT plot, the PAE, PFP and PRE increased as P application rate increased when P was applied as TPR in powder and pellet forms, while the reverse trend was observed with DAP for PAE and PRE.

Table 4.21: Effects of tillage practices and soil amendments on PFP, PAE and PRE in 2013 and 2014

	2013	2014
--	------	------

	PFP	PAE	PRE	PFP	PAE	PRE
	-----kg/kg-----		(%)	----- kg/kg-----		(%)
Tillage Practice						
CR	185.70	168.60	75	179.90	150.40	79
HT	152.70	135.60	51	155.30	125.90	48
FPr	0.07	0.07	0.01	0.10	0.10	0.01
Phosphorus Type (PT)						
Control (No-P)	-	-	-	-	-	-
DAP	239.30	222.10	84	232.50	203	85
TPR (Pellet)	92.70	75.60	39	102.50	73.	44
TPR (Powder)	175.60	158.40	65	167.80	138.30	70
Lsd(0.05)	26.75	26.75	12	28.98	28.98	13
FPr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Phosphorus Rate (PR) kg/ha						
0	-	-	-	-	-	-
11	177.50	157.40	57	180	145.40	63
16	160.90	146.80	69	155.20	130.90	65
Lsd(0.05)	21.84	21.84	10	23.66	23.66	11
FPr	0.12	0.32	0.02	0.04	0.21	0.70
Interactions						
PT x PR	0.01	0.01	0.61	0.31	0.31	0.29
TP x PT	0.94	0.94	0.006	0.27	0.27	0.03
TP x PR	0.45	0.45	0.43	0.57	0.57	0.32
TP x PT x PR	0.56	0.56	0.96	0.15	0.15	0.48
CV (%)	18.60	20.70	24.10	20.30	24.60	23.80

PFP: Partial factor productivity; PAE: Phosphorus agronomic efficiency; PRE: Phosphorus recovery efficiency

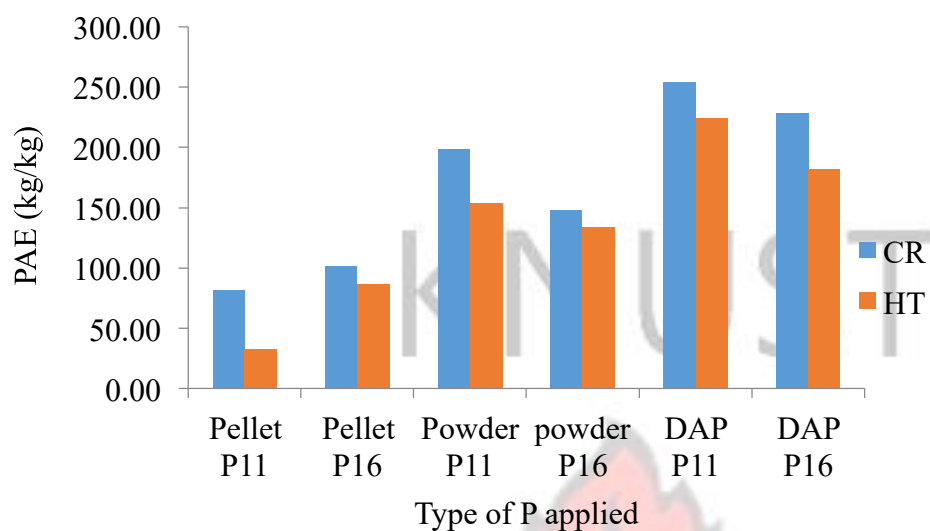


Figure 4.20 Interaction of tillage practices and soil amendments on phosphorus agronomic efficiency in maize in 2013

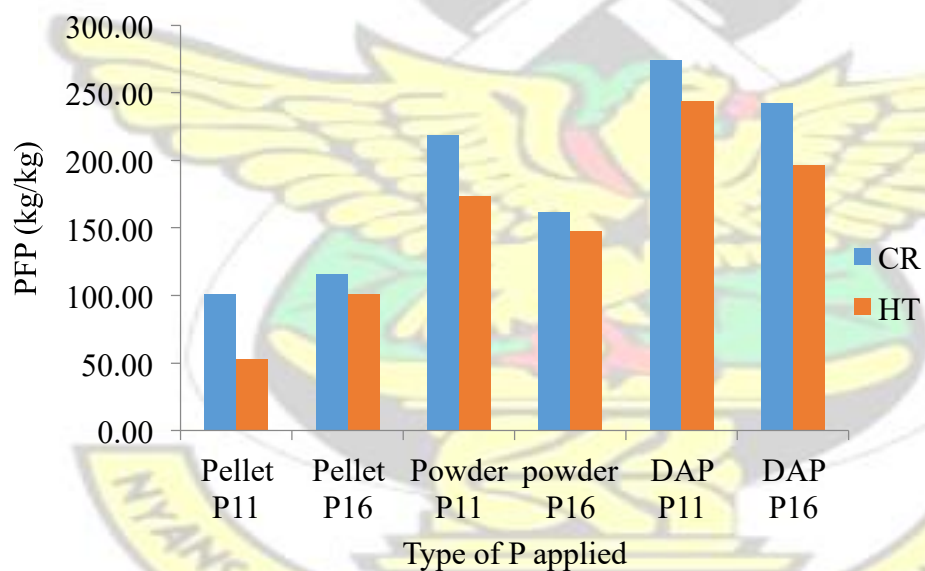


Figure 4.21 Interaction of tillage practices and soil amendments on P partial factor productivity in maize in 2013

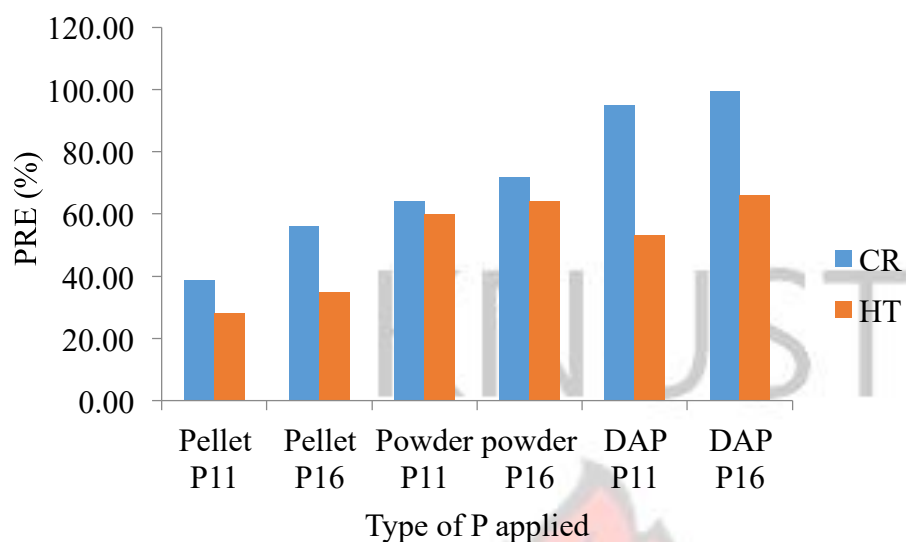


Figure 4.22 Interaction of tillage practices and soil amendments on phosphorus recovery efficiency in maize in 2013

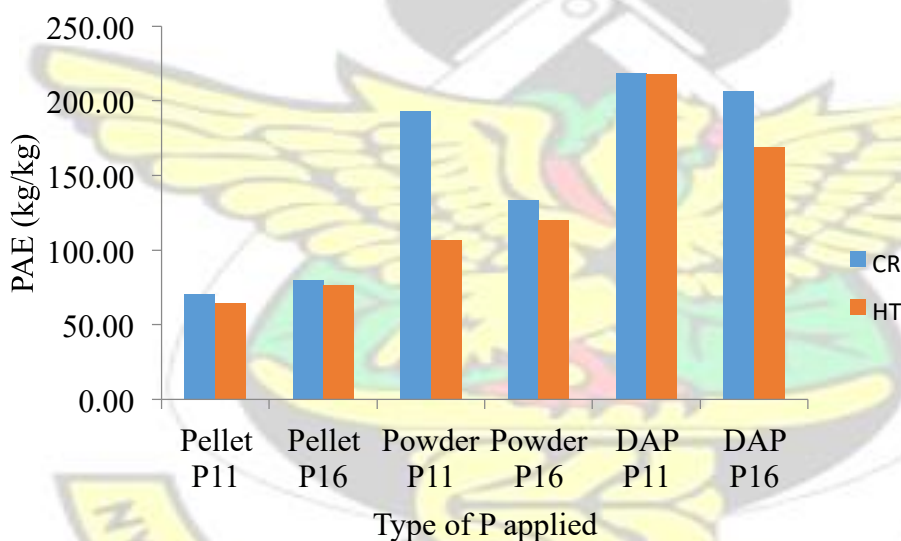


Figure 4.23 Interaction of tillages practice and soil amendements on phosphorus agronomic efficiency in maize in 2014

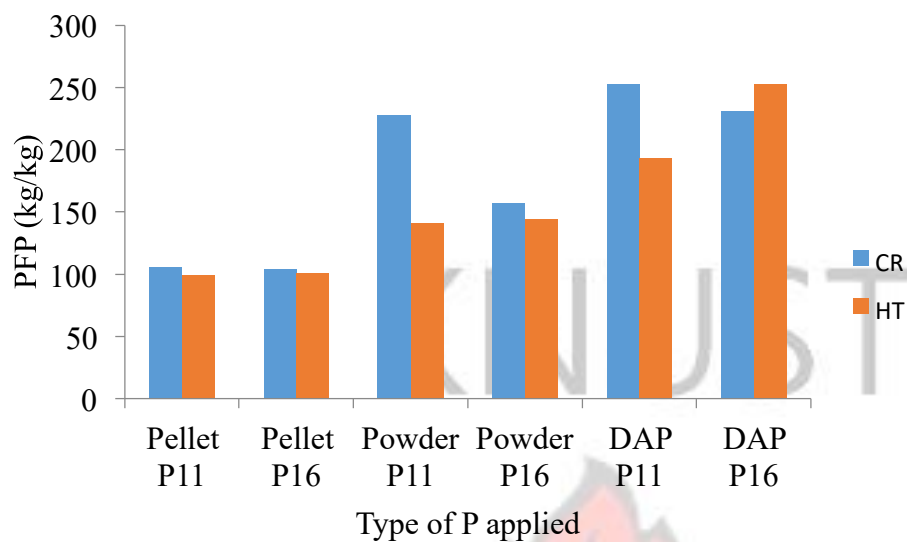


Figure 4.24 Interaction of tillage practices and soil amendements on P partial factor productivity in maize in 2014

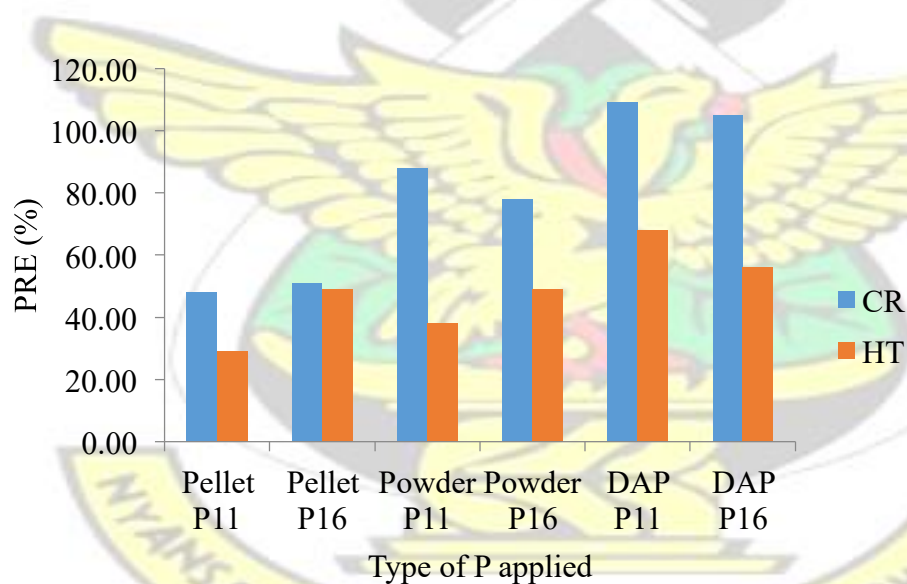


Figure 4.25 Interaction of tillage practices and soil amendements on phosphorus recovery efficiency in maize in 2014

4.2.7.3 Value cost ratio

Under the contour ridge system in 2013, the application of DAP at a higher rate of 16 kg ha⁻¹ produced the highest VCR of 11 (Table 4.22). Value cost ratio recorded under CR was higher than the threshold value of 2 for all the treatments. However, for HT plot, VCR greater than 2 was obtained with the application of DAP and TPR (powder) at 11 and 16 kg ha⁻¹ and TPR (pellet) at 16 kg ha⁻¹. The highest VCR under HT was obtained with DAP at 16 kg ha⁻¹ (Table 4.22).

The VCRs recorded in 2014 were lower than in 2013 (Table 4.22). Values greater than 2 were recorded on TPR amended plots (powder and pellet treated plots) and DAP at 11 and 16 kg ha⁻¹ both for CR and HT.

Table 4.22: VCR of soil amendments and tillage practices for maize cultivation in 2013 and 2014

P types	P rates (kg ha ⁻¹)	VCR			
		2013		2014	
		CR	HT	CR	HT
Pellet	11	3.17	1.37	2.48	2.70
	16	5.53	4.91	4.08	4.32
Powder	11	8.05	6.38	7.58	4.44
	16	8.17	7.56	7.09	6.78
DAP	11	9.37	8.42	7.81	8.20
	16	11.15	9.04	9.86	8.38

1 kg maize = 175 CFA

4.3 Study 3: Assessment of the response of sorghum to different forms of Tilemsi rock phosphate

4.3.1 Effect of soil amendments on sorghum yield and growth

4.3.1.1 Sorghum grain yield

Grain yield was significantly ($P < 0.001$) influenced by soil amendments in both cropping seasons (Table 4.23) of the study in a decreasing order of $P+SAM > P+K$ $+SAM > P+K > Pellet > control$ in 2013, while in 2014, $P+SAM > P+K$ $+SAM > Pellet > control > P + K$ was observed. The interaction between types of phosphorus fertilizer and rate of P applied significantly ($P < 0.001$) influenced the sorghum grain yield in both seasons (Table 4.23)

In 2013, there was an increase in sorghum grain yield from low rate of P application to high rate for all the amendments. At P_0 , no significant difference was observed among the different amendments (Figure 4.26). $P+SAM$ produced significantly higher grain yield than the sole application of TPR as pellet and the control at 11 kg P ha^{-1} (Figure 4.26). However, no significant difference was observed between $P+SAM$, $P+K+SAM$ and $P+K$. At P_{16} , $P+SAM$ produced significantly higher grain yield than the other amendments while $P+K+SAM$ and $P+K$ produced significantly higher value than the control (Figure 4.26). No significant difference ($P > 0.05$) was observed between sole application of TPR as pellet and the control.

In 2014, a general increase in sorghum grain yield was observed with increased P application as observed in 2013. No significant difference was observed among the different amendments at P_0 while significant difference was observed between $P+SAM$ and the control at P_{11} (Figure 4.27). When P was applied at 16 kg ha^{-1} , significant

differences were observed between P+SAM and P+K+SAM compared to sole application of TPR as pellet, P+K and the control (Figure 4.27). No significant difference was observed between sole application of TPR as pellet, P+K and the control (Figure 4.27).

4.3.1.2 Sorghum biomass yield

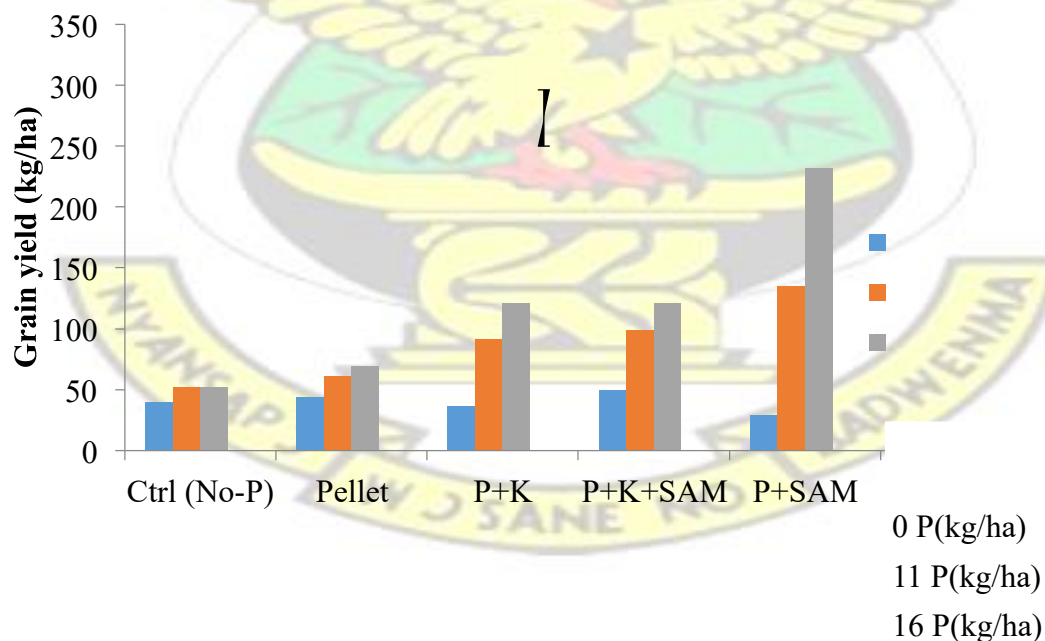
Soil amendments significantly ($P < 0.001$) influenced sorghum biomass yield in both seasons of the study (Table 4.23) in a decreasing order of $P+SAM > P+K+SAM > Pellet > Control > P + K$.

The interaction between types of phosphorus fertilizer and rate of P applied significantly influenced ($P < 0.002$) sorghum biomass yield in both seasons (Table 4.23).

In the first year of experimentation, there was a general increase in sorghum biomass yield from low rate of P application to high rate for P+SAM, P+K+SAM and P+K, while for the remaining treatments a slight decline was observed from P 11 to P 16 kg. No significant difference was observed among amendments at P0 (Figure 4.28). The treatments P+K+SAM and sole application of TPR gave significant higher value when compared to P+K, whereas no significant difference was observed between P+K+SAM, P+SAM and sole application of TPR at P11 (Figure 4.28). At P16, P+SAM and P+K+SAM produced significantly ($P < 0.05$) higher biomass yield than all other amendments (Figure 4.28). No significant difference was observed between sole TPR, P+K and the control in 2013. The trend observed in 2014 was similar to that in 2013, except that no significant difference was observed among the different treatments at P11 (Figure 4.29).

Table 4.23: Effect of soil amendments on sorghum grain and biomass yields

Treatments Phosphorus Type (PT)	2013		2014	
	Grain	Biomass	Grain	Biomass
	----- (kg ha ⁻¹) -----			
Control (No-P)	48.20	413	262	445
Pellet	58.10	702	338.20	713
P+K	82.90	367	253	441
P+SAM	132.40	969	457	986
P+K+SAM	89.80	920	405	949
Lsd (0.05)	26.67	288.80	91.3	297.40
Fpr	<0.001	<0.001	<0.001	<0.001
Phosphorus Rate (PR) kg/ha				
0	39.80	333	213	356
11	87.80	709	371	763
16	119.2	980	446	1001
Lsd (0.05)	20.66	223.70	70.70	230.40
Fpr	<0.001	<0.001	<0.001	<0.001
Interaction PT x PR				
Fpr (0.05)	<0.001	0.002	0.001	0.002
CV (%)	33.60	44.40	27.60	43.60



Type of P applied

Figure 4.26: Interaction effects of phosphorus type and rate of application on sorghum grain yield in 2013

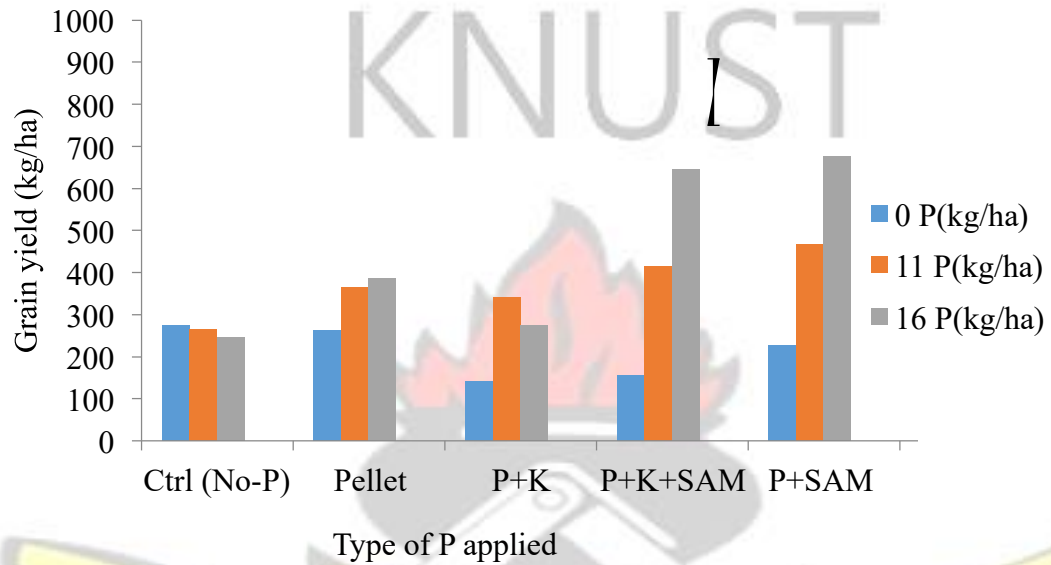


Figure 4.27: Interaction effects of phosphorus type and rate of application on sorghum grain yield in 2014

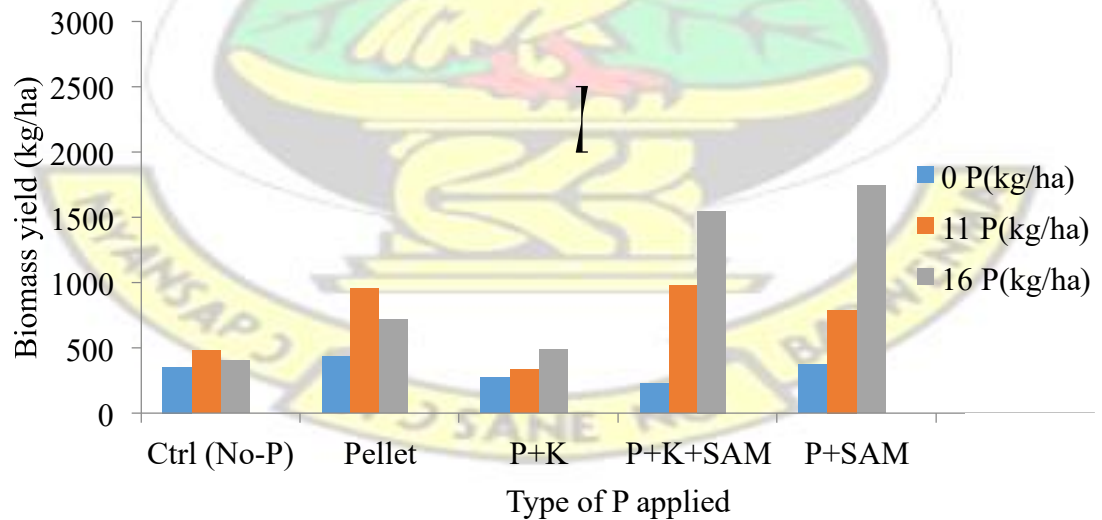


Figure 4.28: Interaction effects of phosphorus type and rate of application on sorghum biomass yield in 2013

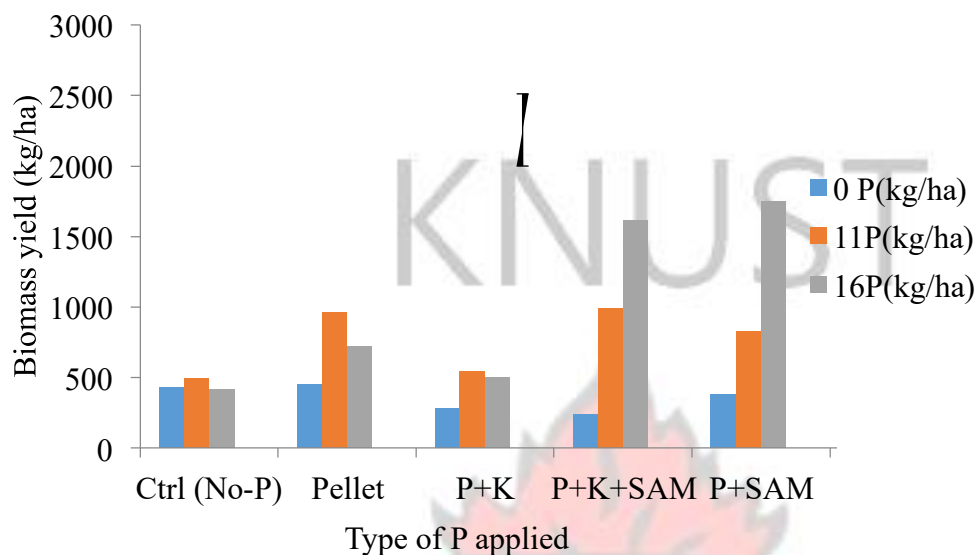


Figure 4.29: Interaction effects of phosphorus type and rate of application on biomass yield in 2014

4.3.2 Effect of soil amendments on soil chemical properties

4.3.2.1 Soil pH

Amended plots did not differ significantly in pH despite the TPR application in 2013, but significantly ($P < 0.001$) influenced the soil pH in 2014 (Table 4.25). Soil pH in 2014 ranged from 3.80 to 4.88. The pH recorded under the different types of TPR was significantly higher than that of the control (Table 4.25). No significant differences were observed among the different types of TPR applied in both years (Tables 4.24 and 4.25). The impact of TPR applied on soil pH was in the order: $P+SAM > Pellet > P+K > P+K+SAM > Control$ in 2014.

Considering the rates of phosphorus application, no significant difference was observed in soil pH under phosphorus applied at 11 and 16 kg ha⁻¹. The two rates however, differed

significantly ($P < 0.001$) from the control in 2014 (Table 4.25), while no significant difference ($P > 0.05$) was observed among the three (including the control) rates of P application in 2013 (Table 4.24).

4.3.2.2 Soil organic carbon and total nitrogen

Soil amendments did not show any significant impact on SOC (Tables 4.24 and 4.25). Likewise, no significant differences were observed between the three rates of P applied in both seasons (Tables 4.24 and 4.25). The interaction between type of phosphorus and rate of P applied did not affect significantly SOC in both seasons.

Like organic C, soil amendments did not show any significant impact on soil total N in 2013 (Table 4.24). However, in 2014 significant differences were observed among the different types of TPR applied (Table 4.25). The phosphorus applied as P+SAM gave significantly ($P < 0.001$) higher N value when compared to the other treatments. No significant differences were observed among P+K+SAM, P+K, pellet and the control. In 2014, significant ($P < 0.04$) difference was observed between P applied at 16 kg ha^{-1} compared to the other rates of P application, while no significant difference was observed between P applied at 11 kg ha^{-1} and P_0 (Table 4.25). In 2013, no significance difference was observed between the three rates applied (Table 4.24).

4.3.2.3 Soil available phosphorus

As expected, soil available phosphorus was significantly ($P < 0.001$) influenced by the soil amendments in both seasons (Tables 4.24 and 4.25). Soil available phosphorus ranged from 2.85 to 5.46 mg kg^{-1} and 2.34 to 4.51 mg kg^{-1} in 2013 and 2014, respectively. In 2013, P+SAM treated plot produced significantly ($P < 0.001$) higher available P value than P+K+SAM, P+K and the control. P+K+SAM and P+K treated plots recorded higher

available P value than the control (Table 4.24). However, no significant difference was observed among P+K+SAM, P+K and sole application of TPR as pellet. In 2014, significant difference ($P < 0.001$) was observed between the control and TPR amended plots. P+K+SAM gave significantly ($P < 0.001$) higher value than P+K and sole application of TPR as pellet. No significant difference was observed between P+SAM and P+K+SAM (Table 4.25). In 2013, the decreasing order of the impact of phosphorus fertilizer on soil available P was P+SAM > P+K+SAM > P+K > Pellet > Control. A similar trend was observed in 2014 except that P+K+SAM plots produced higher available P value than P+SAM.

The different rates of P applied in both cropping seasons significantly ($P < 0.001$) influenced soil available P content (Tables 4.24 and 4.25). Significant difference was observed between P applied at 11 and 16 kg ha⁻¹ compared to P₀. The difference between the two rates (P₁₁ and P₁₆) was however, not significant ($P > 0.05$) in both seasons (Tables 4.24 and 4.25). The interaction between type of phosphorus fertilizer and rate of phosphorus applied did not show any significant difference with respect to soil available P in both seasons. Available P content recorded in P+SAM and P+K+SAM amended plots (Tables 4.24 and 4.25) were higher than that of the initial value (Table 3.2).

Table 4.24: Effect of soil amendments on soil pH, soil organic carbon, total nitrogen and available P in 2013

	pH	%C	%N	P (mg/kg)
Phosphorus Type (PT)				
Control (No-P)	4.61	0.28	0.01	2.85
Pellet	4.73	0.28	0.01	3.65
P+K	4.68	0.29	0.02	3.92
P+SAM	4.67	0.28	0.02	5.46
P+K+SAM	4.74	0.30	0.02	4.46
Lsd (0.05)	0.19	0.11	0.01	0.83
Fpr	0.65	0.99	0.19	<0.001
Phosphorus rate (PR) kg/ha				
0	4.60	0.29	0.02	2.93
11	4.65	0.28	0.02	4.42
16	4.72	0.30	0.02	4.86
Lsd (0.05)	0.15	0.08	0.008	0.64
Fpr	0.68	0.72	0.22	<0.001
Interaction (PT x PR)				
Fpr (0.05)	0.87	0.85	0.10	0.06
CV (%)	4.30	20.50	24.30	21.20
P+K: (TPR+KCl), P+SAM: (TPR+ Sulphate of amonia); P+K+SAM: (TPR+ KCl + Sulphate of amonia) Pellet: (Sole application of TPR)				

Table 4.25: Effect of soil amendments on soil pH, soil organic carbon, total nitrogen and available P in 2014

	pH	%C	%N	P (mg/kg)
Phosphorus Type (PT)				
Control (No-P)	3.80	0.33	0.01	2.34
Pellet	4.86	0.35	0.01	3.41
P+K	4.76	0.38	0.01	3.52
P+SAM	4.88	0.39	0.02	3.97
P+K+SAM	4.66	0.39	0.01	4.51
Lsd (0.05)	0.46	0.17	0.003	0.79
Fpr	<0.001	0.93	<0.001	<0.001
Phosphorus rate (PR) kg/ha				
0	3.87	0.30	0.01	2.52
11	4.93	0.40	0.01	3.82
16	4.97	0.41	0.02	4.32
Lsd (0.05)	0.36	0.13	0.002	0.61

Fpr	<0.001	0.17	0.041	<0.001
Interaction (PT x PR)				
Fpr	0.25	0.29	<0.001	0.10
CV (%)	10.60	47.90	27.50	23.30

4.3.2.4 Effect of soil amendments on soil exchangeable cations and ECEC

The application of different types of fertilizer to the soil significantly ($P < 0.001$) influenced the soil exchangeable Ca during the two years of experimentation (Tables 4.26 and 4.27). No significant difference was observed among the different types of TPR, but they were significantly higher than the value recorded on control plots in 2013 (Table 4.26). In 2014, a significant difference ($P < 0.001$) was observed between TPR amended plot and the control. P+K treated plot recorded significantly higher ($P < 0.001$) exchangeable Ca value than sole application of TPR as pellet and P+K+SAM (Table 4.27). The decreasing order of the impact of different types of TPR on soil exchangeable Ca in 2014 was $P+K > P+SAM > P+K+SAM > Pellet > Control$. In 2014, there was significantly higher calcium content irrespective of the treatment applied than 2013 as shown by year effect analysis (Appendix 3a). In 2013, the interaction between phosphorus types and rate of phosphorus applied significantly ($P < 0.005$) influenced the soil exchangeable Ca content (Table 4.26). An increase in soil exchangeable Ca value was observed with an increase in P application rate for all P amended plots except for P+K where a decrease from 11 to 16 kg ha⁻¹ was observed (Figure 4.30).

KNUST



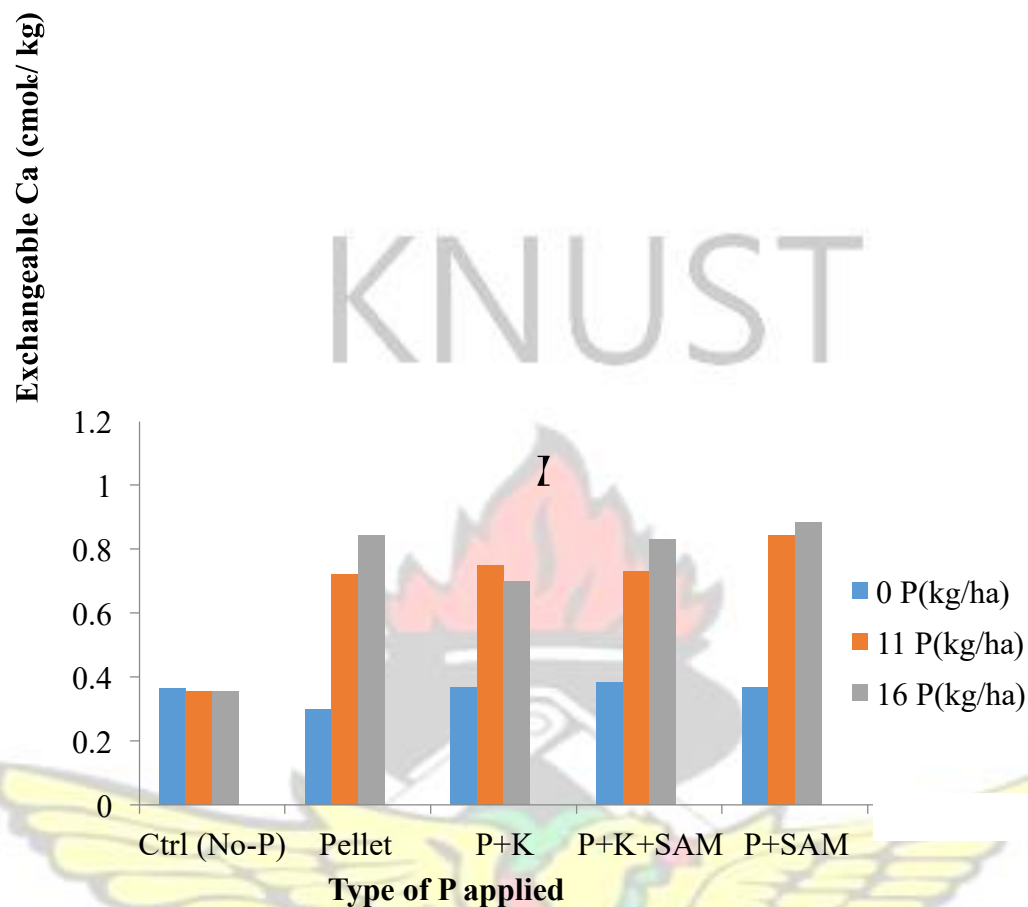


Figure 4.30: Interaction effects of phosphorus type and rate of application on soil exchangeable calcium in 2013

The impact of soil amendments on soil exchangeable Mg is shown in Tables 4.26 and 4.27. Soil amendments significantly ($P < 0.001$) influenced soil exchangeable Mg in 2013, but not in 2014. In 2013, exchangeable Mg was significantly higher under amendments than the control (Table 4.26). Considering the rate of P applied, no significant difference was observed between P11 and P16, while the two rates of P were significantly higher than the control in both seasons.

Like exchangeable Ca, there was an increase ($P < 0.001$) in the Mg content in 2014 over values recorded in 2013 irrespective of the treatments applied (Appendix 3a). The interaction between types and rates of phosphorus fertilizer applied significantly influenced the soil exchangeable Mg in 2013 (Table 4.26). The interaction showed an increase in the exchangeable Mg values as P application rate increased except for P+K

(Figure 4.31).

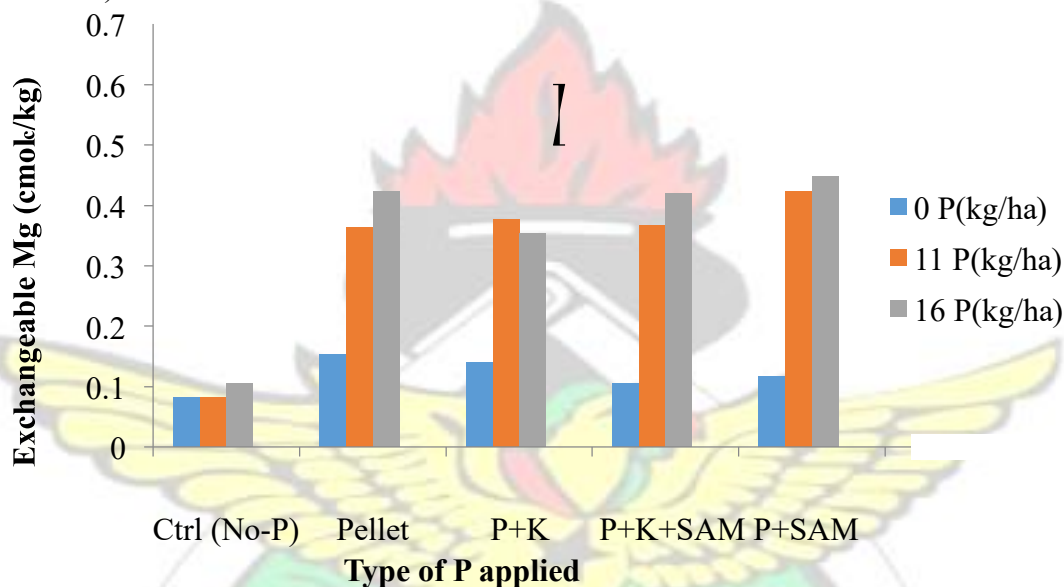


Figure 4.31: Interaction effects of phosphorus type and rate of application on soil exchangeable magnesium in 2013

Significant ($P < 0.001$) difference among amendments was observed in soil exchangeable K during the two growing seasons (Tables 4.26 and 4.27). In 2013, only sole application of TPR as pellet was not significantly different from the control (Table 4.26). In 2014, P+SAM treated plot was significantly higher ($P < 0.001$) compared to the control while, no significant difference was observed among the other treatments (Table 4.27). The interaction between types and rates of P applied significantly ($P < 0.005$) affected soil

exchangeable K in 2013 (Table 4.26). The increase in soil exchangeable K value was observed from 11 kg ha⁻¹ to 16 kg ha⁻¹ for P+K+SAM and P+K, while a slight decrease was observed from P applied at 11 kg ha⁻¹ to 16 kg ha⁻¹ for P+SAM (Figure 4.32).

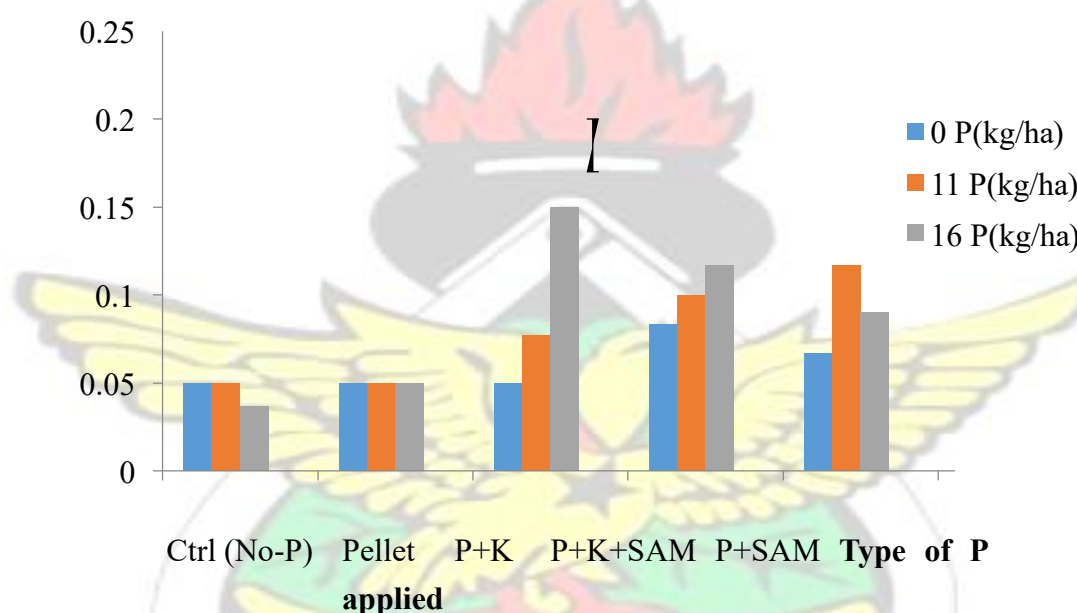


Figure 4.32: Interaction effects of phosphorus type and phosphorus rate of application on soil exchangeable K in 2013

Soil amendments significantly ($P < 0.001$) influenced soil exchangeable acidity in both seasons (Tables 4.26 and 4.27). The application of TPR amendment decreased soil exchangeable acidity compared to the control (Table 4.26). There was a general decrease in exchangeable acidity compared to the initial value recorded before application of the different amendments. The interaction between phosphorus types and phosphorus rates significantly influenced soil exchangeable acidity in 2014 (Table 4.27). Generally, a decrease in soil exchangeable acidity was observed under all the amendments at both 11 and 16 kg ha⁻¹ of P compared to P₀ (Figure 4.33).

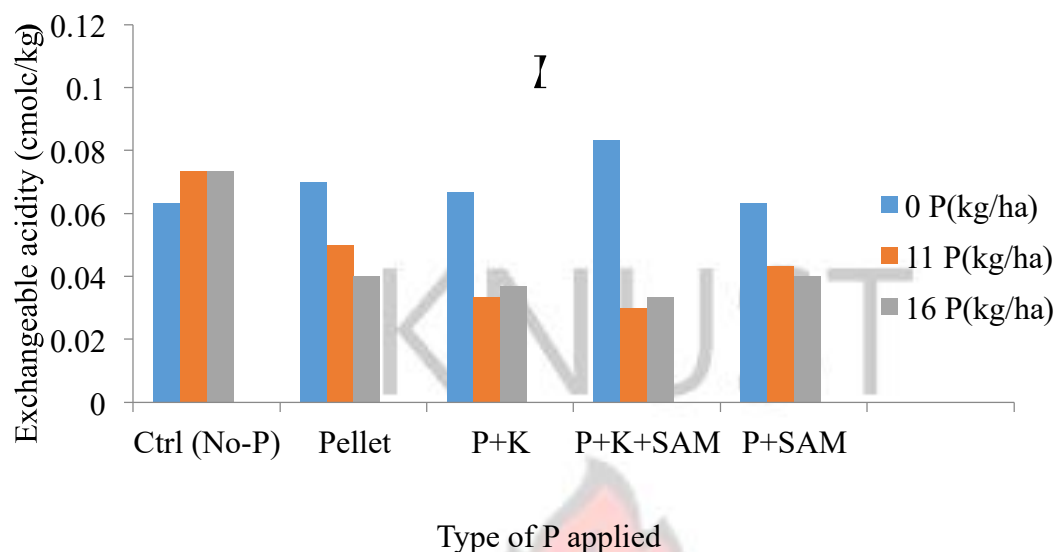


Figure 4.33: Interaction effects of phosphorus type and rate of application on soil exchangeable acidity in 2014

The impact of soil amendments on soil effective cation exchange capacity is shown in Tables 4.26 and 4.27. Effective cation exchange capacity was significantly ($P < 0.001$) influenced by soil amendments in both 2013 and 2014. Though the ECEC values were generally low, there was a general marginal increase in 2014 compared to 2013 as shown by year analysis effect (Appendix 3a) irrespective of the treatment applied. TPR amended plots produced significantly ($P < 0.001$) higher ECEC than the control in the first year. A similar trend was observed in the second year except that no significant difference was observed between sole application of TPR and the control. An increase in ECEC with increase in P rate was observed in both seasons (Tables 4.26 and 4.27). Significantly higher value was recorded under P11 and P16 than the control. The interaction between phosphorus type and phosphorus rate significantly influenced ECEC in 2013 (Table 4.26). Generally, an increase in ECEC was observed under all the amendments as P rate increased (Figure 4.34).

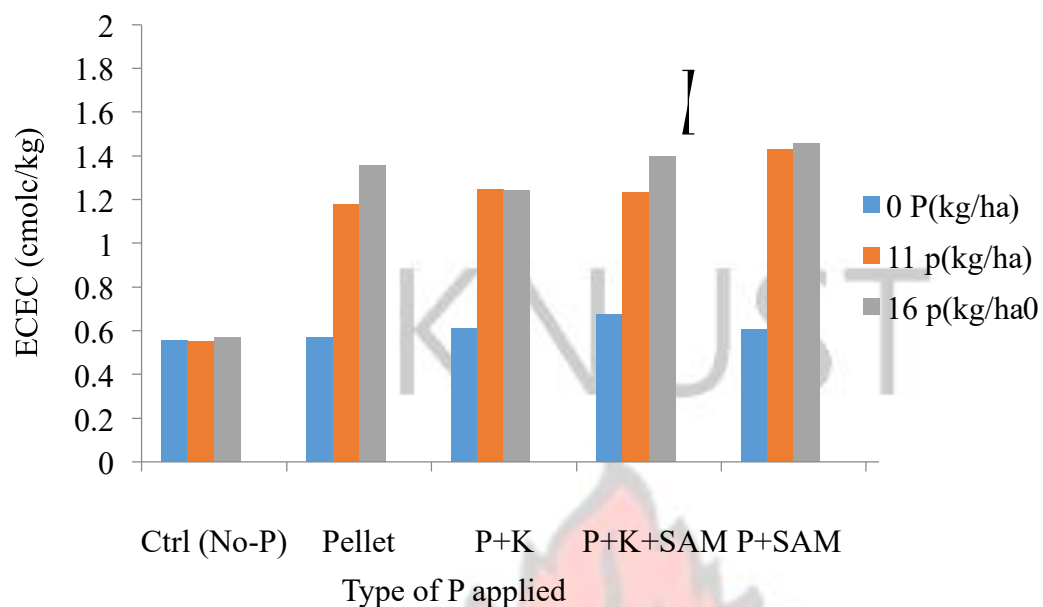


Figure 4.34: Interaction effects of phosphorus type and rate of application on soil ECEC in 2013

Table 4.26: Effect of soil amendments on soil exchangeable cations and ECEC in 2013

	Exch Ca	Exch K	Exch Mg	Exch.Ac	ECEC
Phosphorus Types (PT)	-----cmol+ kg ⁻¹ -----				
Control (No-P)	0.35	0.04	0.09	0.07	0.56
Pellet	0.62	0.05	0.31	0.05	1.03
P+K	0.60	0.09	0.29	0.05	1.03
P+SAM	0.69	0.09	0.33	0.05	1.16
P+K+SAM	0.64	0.10	0.30	0.05	1.10
Lsd (0.05)	0.10	0.02	0.06	0.01	0.17
Fpr	< 0.001	< 0.001	< 0.001	0.01	< 0.001
Phosphorus Rate (PR) kg/ha					
0	0.35	0.06	0.12	0.07	0.06
11	0.67	0.08	0.32	0.05	1.13
16	0.72	0.09	0.35	0.05	1.20
Lsd (0.05)	0.08	0.01	0.05	0.01	0.13
Fpr	< 0.001	0.005	< 0.001	0.004	< 0.001
Interaction PT x PR					
Fpr	0.005	0.003	0.002	0.082	0.007
CV (%)	19.10	29.10	22.90	23.30	18.20

P+K: (TPR+KCl), P+SAM: (TPR+ Sulphate of amonia); P+K+SAM: (TPR+ KCl + Sulphate of amonia) Pellet: (Sole application of TPR)

Table 4.27: Effect of soil amendments on soil exchangeable cations and ECEC in 2014

	Exch Ca	Exch K	Exch Mg	Exch.Ac	ECEC
	-----cmo+1kg ⁻¹ -----				
Phosphorus Type (PT)					
Control (No-P)	0.67	0.08	0.48	0.07	1.35
Pellet	0.98	0.09	0.47	0.05	1.65
P+K	1.26	0.08	0.56	0.05	2.00
P+SAM	1.17	0.10	0.62	0.05	2.00
P+K+SAM	1.05	0.09	0.57	0.05	1.82
Lsd (0.05)	0.20	0.01	0.12	0.01	0.30
Fpr	<0.001	<0.001	0.10	<0.001	<0.001
Phosphorus rate (PR) kg/ha					
0	0.72	0.08	0.43	0.07	1.36
11	1.15	0.10	0.61	0.05	1.97
16	1.19	0.10	0.57	0.04	1.98
Lsd (0.05)	0.15	0.01	0.10	0.01	0.23
Fpr	<0.001	0.006	0.002	<0.001	<0.001
Interaction PT x PR					
Fpr	0.07	0.10	0.71	<0.001	0.39
CV (%)	20.30	11.70	23.60	15.80	17.90

P+K: (TPR+KCl), P+SAM: (TPR+ Sulphate of amonia); P+K+SAM: (TPR+ KCl + Sulphate of amonia) Pellet: (Sole application of TPR)

4.3.3 Effect of soil amendments on phosphorus uptake by sorghum

4.3.3.1 Grain phosphorus uptake

Soil amendments significantly ($P < 0.003$) influenced uptake of P by the sorghum grain during the two growing seasons (Table 4.28).

The interaction between the rate of P application and types of phosphorus significantly ($P < 0.01$) influenced the uptake of P in the sorghum grain in both seasons (Table 4.28). In 2013, no significant difference was observed at P0 and P11 among the different types of phosphorus applied (Figure 4.35). The same observation was made in 2014 (Figure 4.36). When P was applied at 16 kg ha⁻¹, significant difference was observed between

P+SAM and sole TPR (pellet) and P+K+SAM (Figure 4.35), while in 2014, P+K+SAM produced significantly higher grain P uptake values than P+SAM, P+K, TPR (pellet) and the control (Figure 4.36).

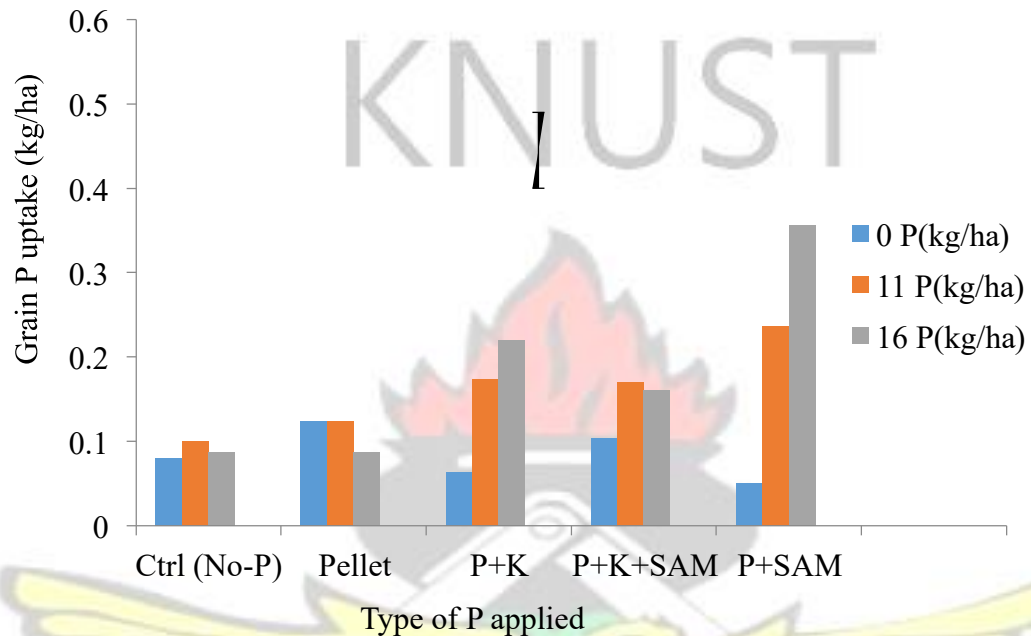


Figure 4.35: Interaction effects of phosphorus type and rate of application on grain P uptake by sorghum grain in 2013

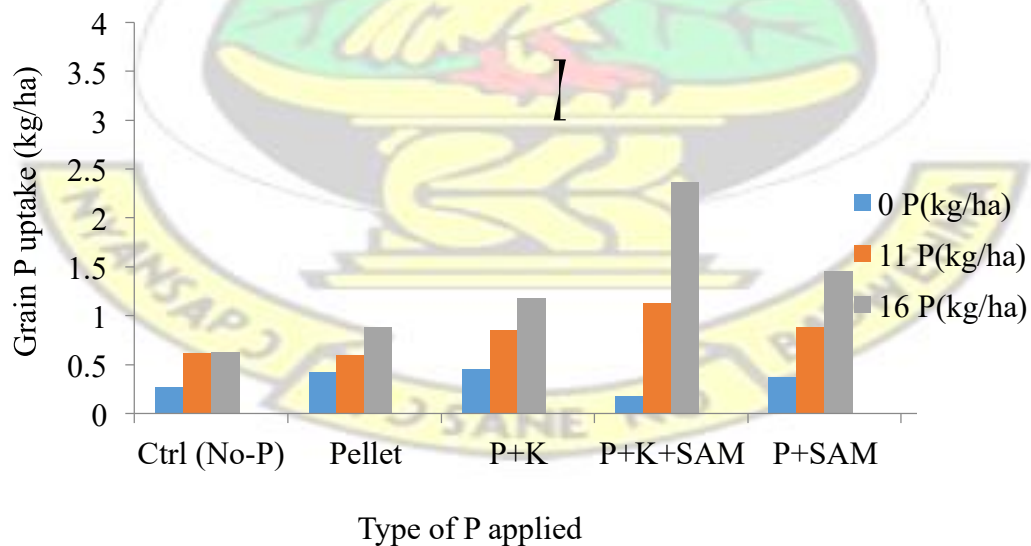


Figure 4.36: Interaction effects of phosphorus type and rate of application on P uptake by sorghum grain in 2014

4.3.3.2 Effect of soil amendments on P uptake by sorghum biomass

Soil amendments significantly ($P < 0.004$) influenced P uptake by sorghum biomass during the two growing seasons (Table 4.28). The interaction of phosphorus application rate and phosphorus type significantly ($P < 0.05$) influenced the uptake of P by sorghum biomass in both seasons (Table 4.28).

In 2013, no significant difference was observed among the different types of phosphorus applied at P0. Significant difference was observed between P+K+SAM compared to P+K at P11 (Figure 4.37). At P16 in 2013, no significant difference was observed between P+SAM and P+K+SAM while they were significantly higher compared to sole application of TPR as Pellet and P+K (Figure 4.37). In 2014 as observed in 2013, no significant difference was observed among the different amendments at P0, the same trend was observed at P11 (Figure 4.38). At P16, P+K+SAM recorded significantly higher values compared to the others, and P+SAM also produced higher significant value compared to sole application of TPR as pellet (Figure 4.38).

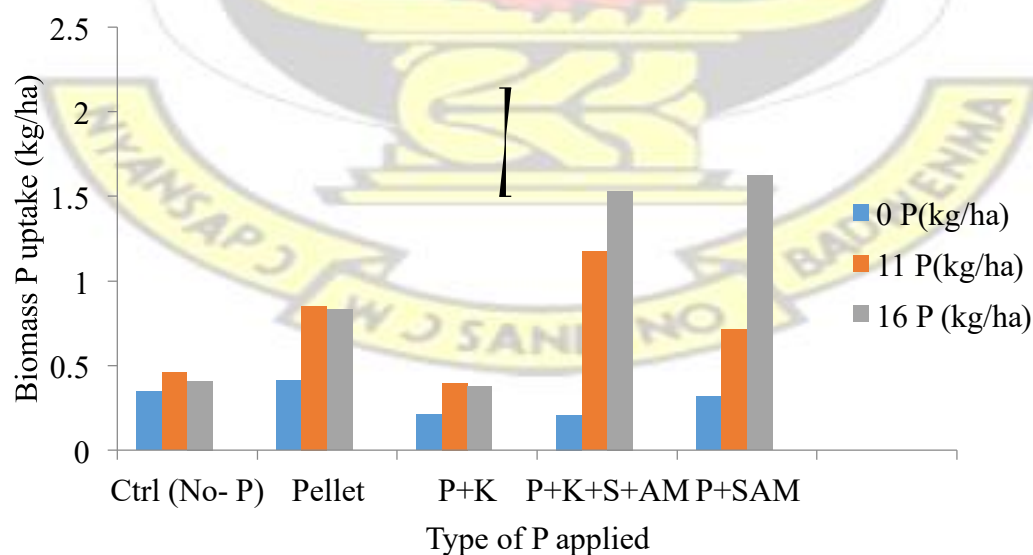


Figure 4.37: Interaction effects of phosphorus type and rate of application on P uptake by sorghum biomass in 2013

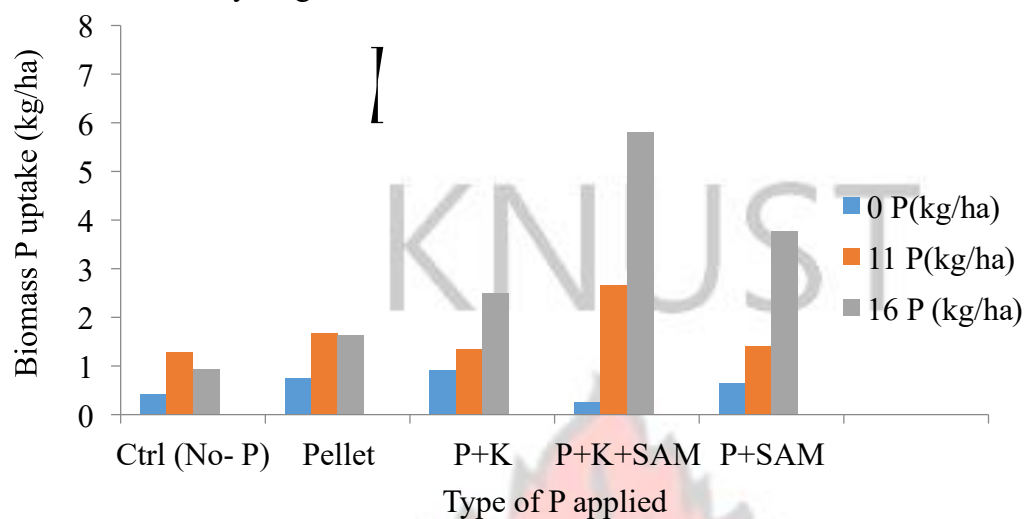


Figure 4.38: Interaction effects of phosphorus type and rate of application on P uptake by sorghum biomass in 2014

Table 4.28: Effect of soil amendments on P uptake by sorghum grain and biomass

Phosphorus Type (PT)	2013		2014	
	Grain	biomass	Grain	biomass
	-----kg/ha ⁻¹ -----			
Control (No-P)	0.09	0.40	0.51	0.87
Pellet	0.11	0.70	0.64	1.34
P+K	0.15	0.32	0.83	1.58
P+SAM	0.21	0.88	0.90	1.93
P+K+SAM	0.14	0.97	1.22	2.91
Lsd (0.05)	0.05	0.37	0.35	0.89
Fpr	< 0.001	0.004	0.003	0.001
Phosphorus rate (PR) kg/ha				
0	0.08	0.30	0.34	0.60
11	0.16	0.78	0.82	1.67
16	0.18	0.95	1.30	2.92
Lsd (0.05)	0.04	0.28	0.27	0.69
Fpr	< 0.001	< 0.001	< 0.001	< 0.001

Interaction PT x PR				
Fpr	< 0.001	0.05	0.01	0.002
CV (%)	38.60	20.90	44.50	53.50

4.3.4 Effect of soil amendments on nitrogen uptake

4.3.4.1 Effect of soil amendments on nitrogen uptake by grain

Soil amendments significantly ($P < 0.001$) influenced the uptake of N by sorghum grain during the two growing seasons (Table 4.29). The interaction of phosphorus application rate and phosphorus type significantly ($P < 0.001$) influenced N uptake by sorghum grain in both seasons (Table 4.29).

In 2013 at P0, no significant difference was noted among the different types of P applied (Figure 4.39). The same trend was found in 2014 (Figure 4.40). At P applied at 11 kg ha⁻¹ in 2013 significant difference was observed between P+SAM compared to P+K and Pellet (Figure 4.39). The same trend was noted in 2014 (Figure 4.40). When P was applied at 16 kg ha⁻¹ in 2013, significant difference was found between P+SAM and the others treatments. Furthermore P+K+SAM produced significantly higher N uptake of the grain than sole application of TPR as pellet and control (Figure 4.39). In 2014, P+SAM and P+K+SAM produced significantly higher N uptake than the P+K, sole application of TPR and the control (Figure 4.40).

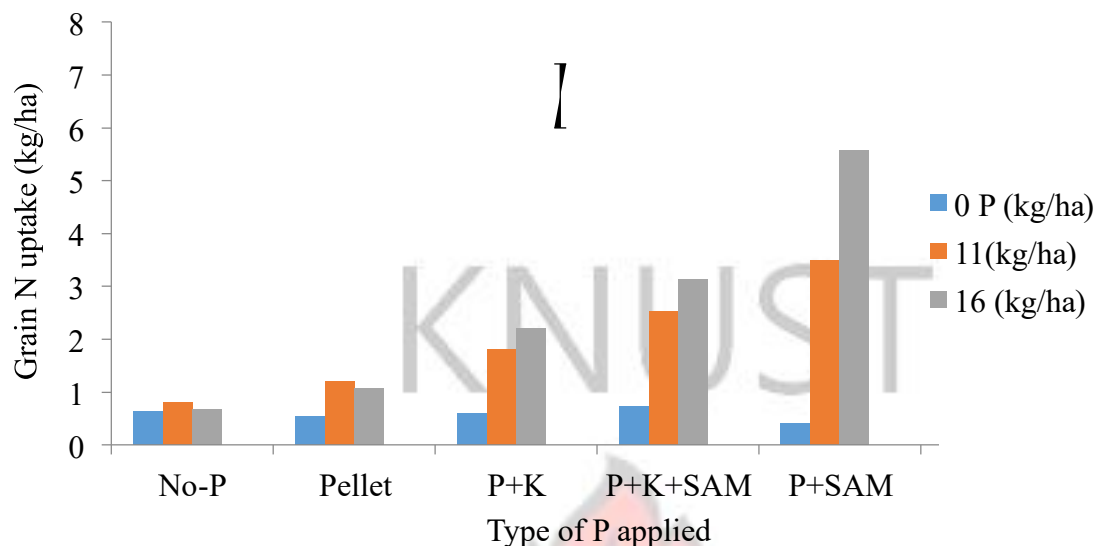


Figure 4.39 Interaction effects of phosphorus type and rate of application on N uptake by sorghum grain in 2013

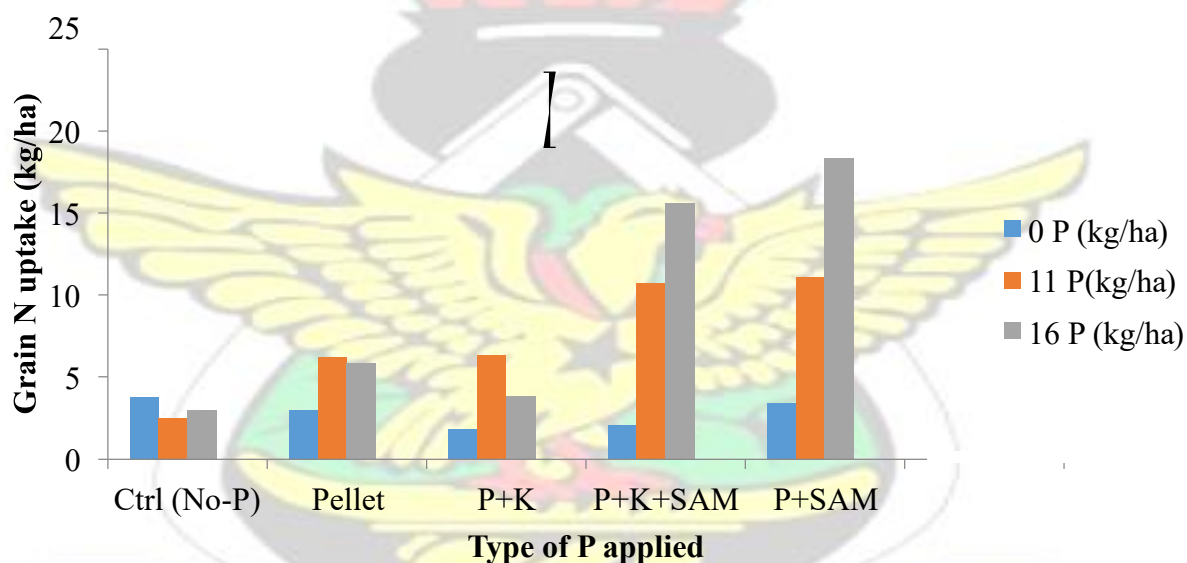


Figure 4.40 Interaction effects of phosphorus type and rate of application on N uptake by sorghum grain in 2014

4.3.4.2 Effect of soil amendments on nitrogen uptake by sorghum biomass

Soil amendments significantly ($P < 0.001$) influence N uptake by the sorghum biomass during the two growing seasons (Table 4.29).

Phosphorus rates and types interacted to significantly ($P < 0.001$) influence sorghum biomass N uptake in both seasons (Table 4.29). In both 2013 and 2014, no significant difference was found between the different types of TPR applied at P0 and P11. When P was applied at 16 kg ha^{-1} , P+SAM and P+K+SAM significantly produced higher N uptake ($P < 0.05$) than the P+K, sole application of TPR and the control in both years (Figures 4.41 and 4.42).

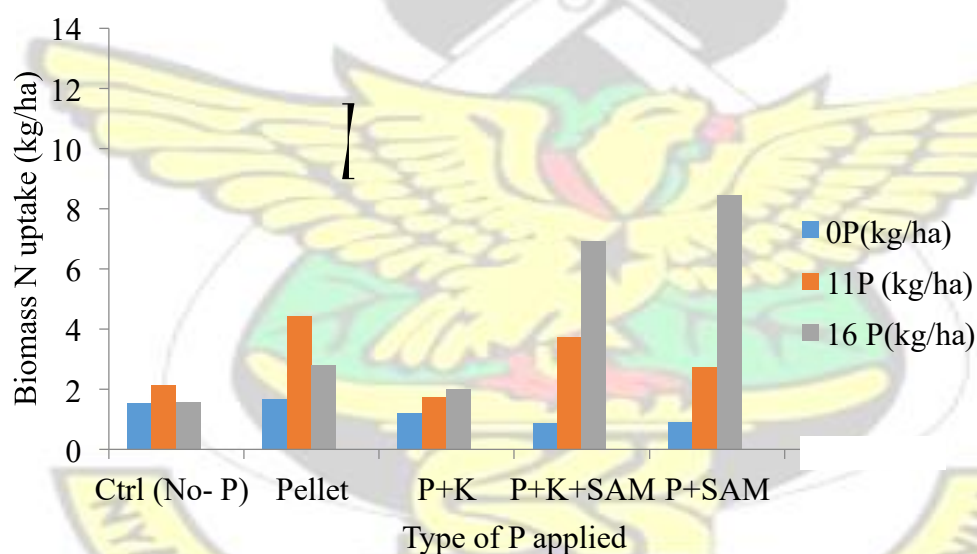


Figure 4.41 Interaction effects of phosphorus type and rate of application on N uptake by sorghum biomass in 2013

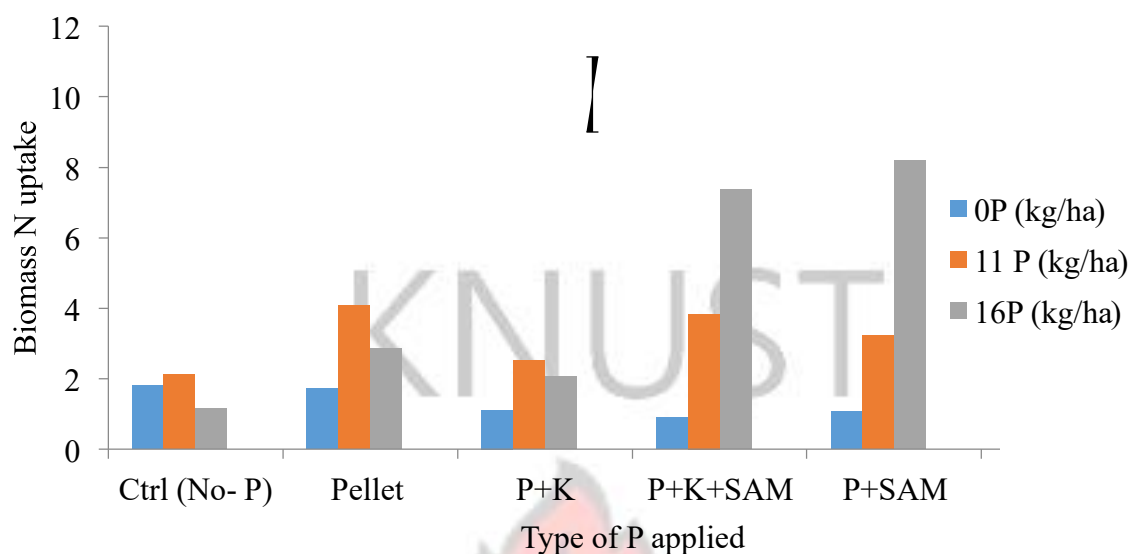


Figure 4.42 Interaction effect of phosphorus type and rate of application on N uptake by sorghum biomass in 2014

Table 4.29: Effect of soil amendments on N uptake by sorghum grain and biomass

Phosphorus Type (PT)	2013		2014	
	Grain	Biomass	Grain	Biomass
	-----kg ha ⁻¹ -----			
Control (No-P)	0.70	1.76	3.10	1.69
Pellet	0.94	2.98	5.01	2.89
P+K	1.54	1.65	3.99	1.90
P+SAM	3.16	4.04	10.94	4.17
P+K+SAM	2.13	3.85	9.46	4.03
Lsd (0.05)	0.70	1.43	2.64	1.23
Fpr	<0.001	0.003	<0.001	<0.001
Phosphorus rate (PR) kg/ha				
0	0.59	1.25	2.81	1.33
11	1.97	2.96	7.38	3.15
16	2.53	4.36	9.32	4.33
Lsd (0.05)	0.54	1.11	2.05	0.95
Fpr	<0.001	<0.001	<0.001	<0.001
Interaction PT x PR				

Fpr	<0.001	<0.001	<0.001	<0.001
CV (%)	42.80	52	42.20	43.40

4.3.5: Correlation between sorghum grain yield, biomass yield, and some soil properties after harvesting

Table 4.30 shows the relationship between sorghum grain and biomass yields and some soil chemical properties. All soil properties were positively correlated with grain yield in both seasons. However, no significant correlation ($P > 0.05$) was observed between grain yield and soil pH in 2013. Biomass yield correlated significantly and positively with available P, exchangeable Ca, K and Mg in 2013, while in 2014 all mentioned soil parameters correlated positively with biomass yield.

Table 4.30: Relationship between sorghum grain and biomass yields, and some selected soil properties at harvest in 2013 and 2014

Soil properties	Grain yield		Biomass yield	
	2013	2014	2013	2014
pH	0.17 ^{NS}	0.57 ^{***}	0.35 ^{NS}	0.54 ^{***}
Total N	0.30 [*]	0.64 ^{***}	0.26 ^{NS}	0.59 ^{***}
Av.P	0.72 ^{***}	0.56 ^{***}	0.63 ^{***}	0.48 ^{***}
Exch.Ca	0.67 ^{***}	0.63 ^{***}	0.64 ^{***}	0.56 ^{***}
Exch.K	0.50 ^{***}	0.62 ^{***}	0.39 ^{**}	0.55 ^{***}
Exch. Mg	0.66 ^{***}	0.60 ^{***}	0.64 ^{***}	0.55 ^{***}

NS: Not significant, *: significant at $P < 0.05$, **: significant at $P < 0.005$, ***: Significant at $P < 0.001$

The relationship between grain yield and selected soil properties is described by multiple regression as shown in Table 4.31. The sorghum grain yield was not significantly ($P > 0.05$) influenced by the different soil properties except soil available P. The analysis

showed that soil available P had significant ($P < 0.05$) positive impact on sorghum grain yield in 2013 compared to other measured properties. The properties that had significant impact on sorghum grain yield in 2014 were total nitrogen and exchangeable K (Table 4.32).

Table 4.31: Multiple regression of grain yield with some selected soil properties in 2013

Soil properties	Coefficients	Standard error	Significance
Constant	-164	149	0.27
pH	238	31.20	0.45
Total N	214	530	0.68
Av.P	16.08	6.34	0.01
Exch Ca	133	114	0.25
Exch K	166	196	0.40
Exch.Mg	96	177	0.59

$$Y_{\text{Yield}} = 16.08 (\pm 6.34) \text{ Av.P} \quad P < 0.001 \quad R^2 = 0.54$$

Table 4.32: Multiple regression of grain yield and some selected soil properties in 2014

Soil properties	Coefficients	Standard error	Significance
Constant	-406	122	0.002
pH	29.80	32.7	0.36
Total N	1076	3419	0.003
Av.P	18.10	18.1	0.32
Exch Ca	40.20	78.7	0.61
Exch K	2517	1277	0.05
Exch.Mg	249	166	0.14

$$Y_{\text{Yield}} = -406 (\pm 122) + 1076 (\pm 3419) \text{ Total N} + 2517 (\pm 1277) \text{ Exch K} \quad P < 0.001 \quad R^2 = 0.64 \quad \text{Av.P: Available P}$$

4.3.6 Relationship between available P, crop growth parameters and some soil properties

Table 4.33 shows the impact of some selected soil properties and sorghum growth factors on soil available P. Highly significant correlation was found between available P and crop growth rate evaluated at period C1 and C2. ECEC, grain nitrogen uptake, biomass nitrogen uptake, total nitrogen uptake and sorghum height also had significant relationship

with available P in both seasons. Exchangeable acidity was negatively correlated with soil available P in both seasons. Soil pH was positively correlated with soil available P in both seasons, but the impact in 2013 was not significant.

A multiple regression function describing the relationship between selected measured parameters and soil available P as shown in Tables 4.34 and 4.35. The earlier rapid growth of sorghum (C1) and sorghum total N uptake significantly ($P < 0.05$) influenced the soil available P in both seasons.

Table 4.33: Correlation between available P, some soil properties and sorghum growth factors

Parameters	Correlation Coefficient	
	2013	2014
C1	0.85***	0.61***
C2	0.66***	0.64***
ECEC	0.73***	0.51***
G N-UP	0.77***	0.61***
Bio N-UP	0.57***	0.48***
Total N-UP	0.68***	0.59***
Height	0.33*	0.36*
Exch.ac	-0.42**	-0.63***
pH	0.16 ^{NS}	0.65***

NS: not significant, *** Significant at $P < 0.001$, ** Significant at $P < 0.01$, * Significant at $P < 0.05$, C1: crop growth rate at 21-42 DAS, C2: crop growth rate at 4364 DAS, GN-UP: Grain N uptake, Bio N-UP: Biomass N uptake, Total N-UP: Total N uptake, Exch.ac: Exchangeable acidity

Table 4.34: Multiple regression analysis between available P, sorghum growth factors and some soil properties in 2013

Parameters	Coefficients	Standard error	Significance
Constant	-2.37	3.40	0.49

C1	0.4280	0.0980	< 0.001
C2	-0.0044	0.0158	0.78
ECEC	1.90	0.477	< 0.001
G N-UP	-57.9	23.5	0.01
Bio N-UP	-58.2	23.5	0.01
Total N-UP	58.1	23.5	0.01
Height	-0.188	0.354	0.59
Exch.ac	11.06	9.24	0.23
pH	0.636	0.643	0.32

$Y_{Av.P} = 0.4280 (\pm 0.0980) C1 + 1.90 (0.477) ECEC - 57.9 (23.5) G N-UP - 58.2 (23.5) Bio N-UP + 58.1 (23.5) Total N-UP$ $P < 0.001$ $R^2 = 0.73$

Table: 4.35 Multiple regression analysis between available P, sorghum growth factors and some soil properties in 2014

Parameters	Coefficients	Standard error	Significance
Constant	-2.79	1.99	0.16
C1	0.0817	0.0366	0.03
C2	0.0126	0.0151	0.41
ECEC	0.761	0.452	0.10
G N-UP	-0.0853	0.0676	0.21
Bio N-UP	-0.121	0.103	0.24
Total N-UP	0.2305	0.0425	0.002
Height	0.250	0.48	0.63
Exch .ac	12.4	11.8	0.29
pH	0.518	0.262	0.06

$Y_{Av.P} = 0.0817 (0.0366) C1 + 0.2305 (0.0425) Total N-UP$ $P < .001$ $R^2 = 0.72$

4.3.7 Effect of soil amendments on phosphorus use efficiency indices

The effect of phosphorus fertilizer application on sorghum partial factor productivity (PFP), phosphorus agronomic efficiency (PAE) and phosphorus recovery efficiency (PRE) are presented in Tables 4.36 and 4.37. Soil amendments significantly influenced ($P < 0.01$) PFP, PAE and PRE in both seasons. In 2013, the application of P+SAM produced

significantly ($P < 0.001$) higher values for both PFP and PAE when compared to P+K+SAM, P+K, sole application of TPR and the control. However, no significant difference was observed between P+K+SAM and P+K, while the two was significantly different from the sole application of TPR as pellet for both PFP and PAE. No significant difference in PRE was observed between P+SAM and P+K+SAM but values recorded under the two were significantly higher than that of P+K (Table 4.36).

In 2014, for PFP, significant difference was observed between P+SAM and P+K, while no significant difference was observed among P+SAM, P+K+SAM and pellet. For PAE, P+SAM and P+K+SAM gave significantly higher values ($P < 0.05$) than values obtained under pellet and P+K. Generally, increase in rate of phosphorus application was found to decrease different efficiency indices evaluated but differences were not significant in 2013 (Table 4.36).

Table 4.36: Effect of soil amendments on partial factor productivity, phosphorus agronomic efficiency and phosphorus recovery efficiency in 2013

Phosphorus Type (PT)	PFP ----- (kg/kg) -----	PAE -----	PRE (%)
Control (No-P)	-	-	-
Pellet	4.99	1.90	4.80
P+K	8.01	4.92	2.00
P+SAM	13.56	10.46	8.10
P+K+SAM	8.36	5.26	9.10
Lsd (0.05)	2.99	2.99	5.20
Fpr	< 0.001	< 0.001	0.04
Phosphorus rate (PR) kg/ha			
0	-	-	-
11	8.79	5.15	5.70
16	8.67	6.12	6.30
Lsd (0.05)	2.12	2.11	3.60
Fpr	0.90	0.34	0.74
Interaction PT x PR	P rates (kg ha ⁻¹)		

Pellet	11	5.54	1.90	5.60
	16	4.43	1.88	4.00
P+K	11	8.31	4.67	2.30
	16	7.71	5.16	1.60
P+SAM	11	12.97	8.65	5.60
	16	14.81	12.26	11
P+K+SAM	11	9.00	5.36	9.30
	16	7.17	5.16	9
Lsd (0.05)		4.24	4.23	7.39
Fpr		0.50	0.50	0.53
CV (%)		27.70	43.00	69.90

PFP: Partial factor productivity, PAE: Phosphorus agronomic efficiency, PRE: Phosphorus recovery efficiency

Table 4.37 Effect of soil amendments on partial factor productivity, phosphorus agronomic efficiency and phosphorus recovery efficiency in 2014

		PFP	PAE	PRE
		----- (kg/kg) -----	-----	(%)
Phosphorus Type (PT)				
Control (No-P)				
Pellet		-	-	-
P+K		32.4	11.99	20
P+SAM		27.6	7.16	15
P+K+SAM		42.8	28.07	28
Lsd (0.05)		39.4	23.13	40
Fpr		9.99	5.92	10
Phosphorus Rate (PR)				
0		-	-	-
11		39.5	16.73	22.90
16		31.6	18.45	28.70
Lsd (0.05)		7.06	4.19	7.50
Fpr		0.031	0.39	0.12
Interaction PT x PR P rates(kg ha ⁻¹)				
Pellet	11	40.20	16.21	23.60
	16	24.67	7.77	16.30
P+K	11	37.80	13.70	20
	16	17.47	1.61	10
P+SAM	11	42.46	20.77	17
	16	43.20	35.37	39
P+K+SAM	11	37.71	16.23	31
	16	41.15	30.02	49.30

Lsd (0.05)	14.13	8.38	15
Fpr	0.05	<0.001	0.009
CV (%)	22.70	27.20	33.40

FPF: Partial Factor Productivity, PAE: Phosphorus Agronomic Efficiency, PRE: Phosphorus Recovery Efficiency

4.3.8 Effect of soil amendments on phosphorus partial balance

Phosphorus partial balance was evaluated in this study in both seasons (Table 4.38). The results showed that during the two years of experimentation, negative P balance was observed when no P was applied to the soil and soil P mining was more pronounced in the second year compared to the first year. When P was applied at the recommended rate (11 kg ha⁻¹), P balance was positive in all TPR amended plots but the amount of P remaining in the soil decreased with cultivation. The same trend was observed when P was applied at 16 kg ha⁻¹. However, the residual P at 16 kg ha⁻¹ was higher than at 11 kg ha⁻¹ in both seasons except for P+K.

Table : 4.38 Phosphate partial balance

P types	P rates (kg ha ⁻¹)	Phosphorus partial balance of P (kg ha ⁻¹)	
		2013	2104
Pellet	0	-0.53	-1.18
	11	10.30	8.73
	16	14.75	13.18
P+K	0	-0.27	-1.35
	11	10.43	8.79
	16	10.05	8.71
P+SAM	0	-0.37	-1.02
	11	10.05	8.71
	16	13.70	10.47
P+K+SAM	0	-0.31	-0.44
	11	9.65	7.20
	16	13.98	7.50

4.3.9 Effect of soil amendments on value cost ratio

The value cost ratio as affected by soil amendments applied is shown in Table 4.39. In 2013, the application of P+SAM at 16 kg ha⁻¹ had the highest VCR of 1.52 whilst the lowest value of 0.55 was obtained with the application of P+K at P11.

In 2014, sole application of TPR as pellet at 16 kg ha⁻¹ had the highest VCR of 4.18 whilst the lowest was recorded under P+K at P16. The VCR recorded in the second year of the study was higher than that for the first year due to higher yield recorded in 2014 than in 2013.

Table 4.39 Effect of soil amendments on value cost ratio (sorghum)

		VCR	
P types	P rate (kg ha ⁻¹)	2013	2014
Pellet	11	0.79	3.36
	16	1.11	4.18
P+K	11	0.55	0.72
	16	0.64	0.51
P+SAM	11	1.02	2.05
	16	1.52	3.17
P+K+SAM	11	0.63	1.49
	16	0.64	2.92
1 kg sorghum = 150 F Cfa			

CHAPTER FIVE

5.0 DISCUSSION

5.1 Study1: Evaluation of standard phosphorus requirement for major soils of Mali

The standard phosphorus requirement for the soils used in this study varied from 7.10 to 24 mg kg⁻¹, with a decreasing order of Longorola > Danga > Niessouman > Konobougou (Table 4.1). The TPR requirement was higher than the recommended rate of TPR used for all the soils. This shows that the amount of phosphorus in soil solution to sustain crop growth and yield when TPR is applied at 11 kg ha⁻¹ would be probably lower than 0.2 mg L⁻¹ and this might have led to decreased crop grain and biomass yields (Table 4.13). Most of the P released from TPR applied at 11 kg ha⁻¹ would be held by soil particles especially in clayey soil. This is particularly true for the soil from Longorola where the amount of P required was 4 times higher than the actual recommendation of TPR used.

The amounts of P required to obtain a concentration of 0.2 mg P L⁻¹ in solution were in the range of 7-10 mg kg⁻¹ of P (16-22 kg ha⁻¹ of P) for the sandy soils (Niessoumana and Konobougou). The low values of SPR recorded (Table 4.1) can be explained by the low level of clay content of the soils. The low clay content of the soil is known to increase TPR dissolution and increase P availability from TPR in soil solution. High phosphorous retention is related to high clay content (Sanchez *et al.*, 2003). Phosphorus in soil solution react with soil minerals and its sorption and desorption process are influenced by soil aggregate size (Wang *et al.*, 2001). Bationo and Mkwunye (1991) and Warren (1992) reported that large areas of Africa, particularly in the semiarid tropics, are dominated by sandy soils with low P sorption and hence low fertilizer P requirements. The authors

reported that a modest annual application of 15 to 20 kg P ha⁻¹ is usually adequate for those soils.

The sorption behavior of the soils studied was adequately described by the Langmuir model. For all the four soils under study, the coefficients of determination (r^2) values were high (≥ 0.78). Langmuir isotherm fitted well with the data set, and when C/X was plotted against C , a straight line was obtained (Appendix 1b). Confirmation of experimental data to the Langmuir equation is believed to indicate that adsorption is the dominant mechanism of P retention (Sample *et al.*, 1980).

In all soils, P adsorption maxima were influenced by some soil properties at varying levels (Table 4.3). The sorption maxima were found to be positively correlated with some soil properties such as clay, OM, exchangeable acidity. The net positive correlation between P adsorption maxima and clay content could be explained by the fact that as the amount of clay increases, the number of fixation sites increases (Aaroon *et al.*, 2013). Phosphorus fixation by clays can be viewed as surface reaction between exposed OH groups on the mineral crystal and the $H_2PO_4^-$ ion or removal of aluminium and iron ions from the edges of the silicate clay crystals for hydroxyl phosphates (Gichangi and Mkeni, 2009).

In this study, soil pH was negatively correlated with Langmuir constant of adsorption (K_L), and a weak correlation was found between pH and P sorption maxima, while negative correlation was found between pH and P_{SPR} (Table 4.3). This result is in close agreement with the report of Dodor and Oya (2000) who observed a weak correlation between P fixed and pH while Kanwar and Grewal (1990) Naidu *et al.* (1990) in their study found a negative correlation between P fixed and pH. The availability of P is mostly dependent on soil pH. Nevertheless, soil pH does not affect phosphorus retention directly, it is a proxy

that shows how minerals such as iron, aluminum, and calcium interact with phosphorus and affect its availability and/ or retention (Pierzynski *et al.*, 2005).

The relatively low SPR values observed in this study can also be explained by the level of available P as in the case of Danga and Niessouman. The relatively high level of available P, in Danga and Niessouman soils ($P \geq 10 \text{ mg kg}^{-1}$) due to utilization of high amount of DAP ($100 \text{ kg ha}^{-1} \text{ year}^{-1}$) possibly accounted for their low SPR values. It has been shown that previous application of P reduces a soil's capacity to adsorb further P due to low movement of P in soil (Koenig *et al.*, 2000). In this respect, Hue and Fox (2010) reported that a portion of the previously added P had been converted into a form which was occupying P adsorption sites, blocking them from further reaction. The authors further reported that with past P fertilization, uncultivated Hali soil sorbed 1.5 times more P than the cultivated soil.



5.2 Study2: Assessment of the efficiency of Tilemsi rock phosphate compared to DAP at different rates of application under different tillage practices

5.2.1 Effect of soil amendments on selected soil chemical properties

5.2.1.1 Soil pH

Soil pH is indicative of soil reaction and it determines the availability of soil nutrients for plants. Soil pH was not significantly affected by tillage practices during the two growing seasons (Tables 4.4 and 4.5). The application of soil amendments significantly influenced soil pH with higher values in TPR amended plots than DAP and no amendment plots. The highest soil pH observed with TPR application can be attributed to self – liming (alkalinity) caused by the dissolution of TPR and release of basic cations. Since the apatite mineral in TPR is Ca-P, there is a potential to provide Ca and Mg nutrients if there are favourable conditions for apatite dissolution. Similar results were reported by Hellums *et al.* (1989) who found an increase in soil pH on strongly acid loam soil after application of TPR. Szilas *et al.* (2007) reported that the application of reactive PRs to soil increased exchangeable Ca and Mg and soil pH. Furthermore, the dissolution of apatite in PR consumes H^+ ions and thus, it can increase soil pH, depending on PR reactivity (FAO, 2004). Increasing TPR application rate led to increased soil pH. The increase in soil pH was directly proportional to the concentration of basic cations added by TPR.

In the second year of the experiment, the general increase in pH at harvest for all the phosphorus types could be explained by the addition of substantial amount of TPR during the two growing seasons and subsequent release of Ca and Mg. The increase in soil pH under DAP plot is in contradiction with the results of Manoharan *et al.* (1995) who

reported an acidification of soil following the application of DAP by the nitrification of NH_4^+ during which H^+ ions are released.

5.2.1.2 Organic carbon

In this study, fertilizer application and tillage practices did not affect the soil organic carbon contents in both seasons (Tables 4.4 and 4.5). This may be due to the short - term nature of the experiment (2 years), though a slight increase in SOC was observed under HT. Studies have previously highlighted the improvement in soil organic carbon content in reduced tillage practice after several years (Dimassi *et al.* 2014; Villarino *et al.* 2014). It has been well documented that increased tillage intensities can reduce soil organic matter in the topsoil due to increased microbial activity and carbon (C) oxidation. The SOC recorded in 2014 was lower than that of 2013 which was comparatively lower than the initial value, indicating a decline of SOC content with cultivation. In an earlier study, Kouyate *et al.* (2012) reported a decline in SOC on Sudanian and Sudano-Sahelian's family farming system, where the decline in the level of carbon was noticed during the years of cultivation.

5.2.1.3 Total N

Soil total N was not significantly affected by soil tillage during the two growing seasons (Tables 4.4 and 4.5). However, slightly higher values were observed under CR compared to the HT in both seasons. This might be due to the relatively high level of soil moisture storage under the former. According to Sleutel *et al.* (2008), in mineral soil, N mineralization is maximal at intermediate levels of soil moisture content (50-70% water-filled pore space).

Moreover, the intensity of tillage under CR is higher compared to HT. CR enhances the incorporation of crop residues into soil, improves soil aeration, and subsequently promotes organic N mineralization. Tangyuan *et al.* (2009) reported that tillage enhances the mineralization of nitrogen (N) by incorporating crop residues, disrupting soil aggregates and increasing aeration. The soil total N as observed in 2014, was higher than in 2013 and the initial value (Tables 4.5 and 4.6). This can be attributed to the decomposition of crop biomass produced in the first year of experimentation by means of tillage practice and soil microbial biomass.

5.2.1.4 Available phosphorus

Available P recorded under CR practice in 2013 was significantly ($P < 0.01$) higher than that of HT (Table 4.4). The same result was observed in 2014 but the difference was not significant. The increase in P availability on contour ridge plot compared to hoe tillage may be ascribed to the relatively high soil moisture content recorded (Tables 4.8 and 4.9) in the former in both seasons. Numerous studies have confirmed the beneficial impact of soil moisture on TRP solubility. Marschner (1995) reported that soil moisture improves crop growth and enhances P and Ca uptake by plants which in turn could increase the rate of solubilization of sparingly soluble P. The displacement of the soil solution equilibrium, increases P transfer from the solid phase to the solution. Increase in the P- sink of the soil or removal by plants increases the rate of TPR dissolution (Straaten, 2002). Also the capacity of CR tillage technology to reduce water destructive runoff compared to HT could explain the higher level of available P under the former than the latter. Gigou *et al.* (2006) and Doumbia *et al.* (2008) reported that CR reduced runoff of seasonal rainfall by 26%.

The effect of CR tillage on phosphorus availability is more pronounced with TPR powder form than the pellet due to the smaller particle size of the former (Figures 4.5 and 4.6).

Soil fertility amendments significantly ($P < 0.001$) influenced the soil available P in both 2013 and 2014. The increase in soil available P depended on the amount of P and type of fertilizer applied. P applied at 16 kg ha^{-1} produced higher available P value than P applied at 11 kg ha^{-1} which clearly contradicts the observation of Bolland (2007). According to this author, when small rates of rock phosphate are applied, the particles are farther apart and so discrete phosphate rock particles react with soil. In such a case each phosphate rock particle will dissolve to its maximum extent in the soil. Low soil solution P concentrations due to high rates of PR have been reported by Rajan *et al.* (1991). High rates of TPR are not desirable as they will introduce more CaCO_3 hence reducing the amounts of proton that would otherwise be available for dissolving P from calcium phosphate in the PR (Mowo, 2000). However, the decision on the rate of TPR application needs to be based on the soil P status as indicated by soil testing (Perrott and Wise, 2000), and the expected rate of dissolution of TPR and its availability to plants (Rajan *et al.*, 1996). The minimum rate of application should be such that the expected amount of P dissolved from PR is no less than the amount of P removed from the soil plus the amount of phosphorus retained by soils in a form that is not available to crops under near maximum production levels (FAO, 2004). In this study, P applied at 16 kg ha^{-1} rate was found to be an optimum rate at which the soil capacity and intensity factor is considered. Below this rate the available P from rock phosphate could not be sufficient to meet crop requirement due to low P in soil solution. In severely P – deficient soils, the soil adsorb almost all of the dissolved P with very little increase in soil solution when low amounts of PR are added (FAO, 2004). Furthermore, P applied at 16 kg ha^{-1} rate was found to be an optimum rate for the study

site (Konbougou). This means that the amount of available proton was enough to support TPR dissolution.

The significantly higher values recorded with DAP at both 11 and 16 kg P ha⁻¹ compared to TPR amended plots could be due to the fact that DAP is a water soluble phosphorus and releases more P in soil solution than TPR. The application of fertilizer P increased soil available P under the two tillage practices in both seasons over the initial of 2.13 mg P kg⁻¹. This can be explained by the low pH < 5.5 (Table 3.2) which is considered a critical level to enhance PR dissolution. Also, clay content of the soil was very low (4.20 %) and this in turn reduced the sorption of available P in the soils study site. Moreover, the low initial soil phosphorus concentration enhanced the dissolution of TPR. Several studies showed the positive impact of low soil pH, low soil phosphorus content and low solution concentration of Ca ion on the dissolution of PR. Bollan and Hedley (1990) reported that lower pH values in the range from 6.5 to 3.9 increased the dissolution of North Carolina phosphate rock (NCPR) from 29.3 % to 83.5 %.

5.2.1.5 Exchangeable cations

Soil exchangeable Ca and Mg were not significantly affected by tillage practice during the two years of experimentation (Tables 4.6 and 4.7). The lowest exchangeable calcium and magnesium contents recorded during the two growing seasons on no amendment plot could be explained by the effect of continuous maize cropping, due to removal of basic cations by harvested crops. This result is in close agreement with the observations of Riffaldi *et al.* (1994) and Juo *et al.* (1996) that continuous cropping resulted in lower exchangeable calcium and usually results in soil acidification.

The increase in soil exchangeable Ca and Mg in the second year of the study in TPR amended plot more than the control may be explained by the continuous dissolution of TRP in acid soil. TRP contains sufficient amount of Ca and Mg which possibly contributed to greater release of Ca and Mg during dissolution process with time. A similar result was reported by Hu *et al.* (1997), following a three year field trial conducted in Central China. The authors reported that Ca increased from 1194 mg kg⁻¹ with the control to 1300–2100 mg kg⁻¹ with PR treatments. The corresponding exchangeable Mg levels were 330 mg kg⁻¹ with the control and 350–400 mg kg⁻¹ with the PR treatments (Hu *et al.*, 1997). However, if dissolution of free carbonates raises pH and exchangeable Ca around PR particles significantly, it can hinder apatite dissolution and thus reduce P availability of PR (Chien and Menon, 1995).

Increasing the rate of phosphorus application significantly increased the soil exchangeable Ca in 2014. The increase in P application rate enhanced the amount of Ca and Mg in soil due to the fact that TPR contain substantial amount of Ca. Moreover, the continual dissolution or residual effect of TPR can also explain the difference in Ca observed in both years. In case of exchangeable K, the slight increase in 2014 over the initial value (0.10 cmol_c kg⁻¹) could be explained by the decomposition of crop residues produced in the first year of experiment. This result is in contradiction with the observation made by Wicks *et al.* (1988) when they found a decline in exchangeable potassium in cultivated soils over time. Srinivasa *et al.* (1999) reported a significant decline in K release due to continuous cropping.

5.2.1.6 Effective cation exchange capacity

The increase in ECEC in the second year compared to the first year can be attributed to the continuous dissolution of TPR which released substantial amount of Ca and Mg in

soil. Similarly, high ECEC under TPR plot than no amendment plot was due to high content of Ca and Mg in TPR. According to Zin *et al.* (2005), PR fertilizers have a higher Ca content which could increase soil pH and effective cation exchange capacity (ECEC). The decline in soil exchangeable bases (Ca and Mg) with cultivation in the no amendment plot (Tables 4.6 and 4.7) can be responsible for the low ECEC value recorded in such plots.

5.2.2 Relationship between some soil properties and available phosphorus at harvest

The lack of significant correlation between soil available P and some soil properties such as exchangeable acidity, SOC and soil moisture content in this study (Table 4.10) can be explained by the low impact of these properties in TPR dissolution. In the case of SOC, the weak correlation may be explained by the low initial value of SOC and by the non addition of any organic material. Several studies have shown the beneficial impact of organic matter on phosphorus availability to crops. Iyamuremye and Dick (1996) and Erich *et al.* (2002) explained increase in soil available P in the presence of organic materials by the fact that soluble organic materials may specifically adsorb to soil minerals by ligand exchange in competition with phosphorus. This can block potential adsorption sites to increase the availability of P originating from both the organic materials and subsequently added fertilizer (Iyamuremye and Dick, 1996). The influence of organic matter on the dissolution of rock phosphate is related to the formation of Ca and organic matter complexes. By reducing Ca activity in the solution (Ca-sink), the phosphate rock dissolution will be increased. Hence the higher the organic matter contents of the soil, the better the dissolution of the PR (Straaten, 2002).

The weak correlation observed between exchangeable Ca and available P especially in the first year (Table 4.10) may be explained by the low solubility of TPR in the short time which did not allow much release of dissolution product from TPR. The significant positive correlation observed between available P and Ca in 2014 in CR (Table 4.10) can be attributed to the increased solubility of TPR with time.

Soil pH had a strong link with soil available P in 2013 and 2014 compared to other soil properties in this study. It had positive impact on soil available phosphorus in CR both seasons while in 2014 it affected positively the available P released from TPR in HT plots (Tables 4.11 and 4.12). The positive impact of pH on phosphorus availability in this study was due to its low values as observed under both CR and HT plots. Phosphate rock dissolution involves the consumption of proton (H^+), and the release of Ca and phosphate ions to soil solution. Consequently, soils with a large source of free protons (acid soils) are suited for PR application (Mowo, 2000). Bolan and Hedley (1990) reported that the use of PRs is recommended in soil with pH 5.5 or less. The authors reported that the dissolution of PR diminishes with increasing pH up to 5.5.

As observed with the different soil properties in this study, lack of significant correlation was observed between soil moisture content and available P during the two years of the experiment (Table 4.10). The frequent long dry spell period (Appendix 6 and 7) observed in the study area following the application of TPR especially at earlier stage of crop growth during the two growing seasons can explain the low impact of soil moisture on phosphorus availability from rock phosphate.

5.2.3 Effects of tillage practices and soil amendments on maize grain and biomass yields

Though not significant, grain and biomass yields were 19 % higher under CR than HT due possibly to the higher soil moisture content under the former. Gigou *et al.* (2006) and Kablan *et al.* (2008) reported that maize grain yield may increase as much as 50 % under CR. Soil moisture conservation is vital for smallholder cropping systems. The conserved moisture supplies water to the crop at the end of the rainy season when plants are flowering and filling their grains.

Soil amendments increased significantly grain and biomass yields over the control plot during the two cropping seasons (Table 4.13). Because of the low inherent soil fertility in the study site, applying plant nutrients (TPR, DAP and Urea) induced positive reaction to crop production, hence the higher yield.

The grain and biomass yields increased significantly as P level increased. This can be explained by the increased availability of P in soil solution for plant uptake from the rhizosphere. The powder form of TPR significantly increased maize grain yield over the pellet form and the application of DAP produced significantly ($P < 0.001$) higher grain yield than P applied as TPR both for P11 and P16. This could be attributed to the nutrient being made readily available from the DAP fertilizer than TPR, and the powder form of TPR than the pellet form. DAP showed superiority over different forms of TPR because of the higher P release capacity. The earlier release of high amount phosphorus (WSP) stimulates early root formation and the ability of plants to absorb water and other nutrients and stimulates flower blooms (Schachtman *et al.*, 1998). However, the higher grain and biomass yields recorded under TPR powder than pellet form may be explained by the differences in particle size between the two fertilizers. The solubility of TPR generally

increases with smaller particle size and consequently, the P release from TPR for crop growth (Chien and Friesen, 1992; FAO, 2004). As PRs are relatively insoluble minerals, their geometric surface area is an important parameter determining their rate of dissolution. The finer the particle size, the greater the geometric surface area and degree of contact between the soil and PR particles and, thus, the greater the PR dissolution rate (FAO, 2004).

5.2.4 Relationship between maize yield and some selected soil properties

Phosphorus has been established to be one of the most limiting plant nutrient in Mali. The soil of the study site was characterized by low inherent soil fertility, with very low level of available P (Table 3.2). The positive and significant correlation between maize grain yield and soil available P can be explained by the addition of sufficient amount of phosphate fertilizers of DAP and TPR during the two growing seasons. The addition of the nutrient on the inherently low fertile soils enhanced crop productivity. The relatively higher soil pH, and nutrient P content and uptake were responsible for the yield performance of amended plots relative to the control. This is confirmed by the positive correlation between these soil factors and maize yields (Table 4.14). Though they contributed to the increase in maize yield under the two tillage practices, their impact under CR plot was higher than HT.

On the other hand, multiple regression analysis showed that available P was the most important soil nutrient that significantly increased maize grain yield in both seasons and for the two tillage options compared to other soil properties. This result confirms that P is one of the most limiting nutrients for crop growth in tropical soils. Application of P is

an absolute necessity, and thus, external inputs other than P may not even be costeffective as long as the P status is not raised to satisfactory levels (Sedogo *et al.*, 1991).

5.2.5 Effects of tillage practices and soil amendemnts on nutrient (N and P) uptake in miaze

Nutrient uptake is the process by which plant root take up nutrients present in the soil solution, with such nutrient subsequently distributed to aerial portions of the plant (Halvin *et al.*, 2005).

Generally, higher nutrient uptake was observed in CR plot compared to HT plot during the two growing seasons (Table 4.17). This observation may be due to the improvement in soil water content under this practice (Tables 4.8 and 4.9). Research findings have demonstrated a positive interaction between soil moisture and P uptake because improved soil moisture status increases soil P availability (Ouattara, 1994). Soil nutrient uptake is highly influenced by the availability of nutrient in the soil. Higher P uptake under CR plot may be attributed to the higher level of available P recorded under CR plot than HT (Table 4.4). The increased level of available P under CR over the HT ranged from 7 to 31 %. Plant P uptake was higher on plot amended with DAP than TPR and the control due to the rapid release of P from the water soluble DAP. The rapid release of P promoted rapid root growth. This might have resulted in increased nutrient uptake and consequently, increased growth and total dry matter production.

PRs are slow releasing fertilizers and they require time and water surrounding the particles in order to enable the dissolution products to diffuse away from the PR particle into the soil. Smilarly, the increase in plant P uptake from TPR applied in powder compared to the pellet form can be explained by the rapid release of P from the former

due to particle size. It is known that fine particle size improves rapid dissolution of TPR and its effectiveness than the pellet form. The rapid release of P from fertilizer stimulates earlier growth and root formation and growth, improves the ability of plants to absorb water and other nutrients (Uchida, 2000).

Increase in P application rates consequently, led to increase in P uptake (Table 4.17) due to more of P in soil solution. The quantity of P that is available for uptake by plants from the soil is related to the concentration of P in the soil solution and P buffer capacity of the soil (Mengel *et al.*, 2001). Fatondji, (2002) and Sharif *et al.* (2014) reported increase in sorghum nutrient uptake with an increase in soil available nutrient content.

Akande (2011) showed that P uptake by maize increased in three different soils in Nigeria as result of P applied at highest level at 60 kg ha⁻¹. The lowest nutrient uptake in the control plots showed the extent of land degradation (nutrient depletion) at the study site.

The relatively high P uptake observed in 2014 than in 2013 (Table 4.17) can be explained by the low initial P level (2.13 mg kg⁻¹) and probably the low pH in the first year of experimentation compared to the second year. Furihata *et al.* (1992) reported that P uptake rate are highest between pH 5.0 and 6.0 where H₂PO₄⁻ dominates. Moreover, the continual dissolution of TPR with release of more P led to higher P uptake in 2014 than in 2013.

5.2.6 Effects of tillage practices and soil amendments on phosphorus use efficiencies by maize

In this study, phosphorus use efficiency values recorded were higher for DAP than TPR forms. Among TPR forms used, the powder form was significantly more efficient than the pellet form under the two tillage practices, suggesting that the particle size exerts positive influence on

phosphate use efficiency. Application of finely ground TPR enhances both the rate of dissolution of PRs and P uptake in a given soil (FAO, 2004). Moreover, the increase in the number of PR particles per unit weight of PR applied increases the chances of root hairs intercepting PR particles (FAO, 2004).

Generally, low rate of P application led to higher P use efficiency indices (PAE, PFP, RAE) than high rate of P application in 2013. In 2014, however, the opposite trend was observed in HT plot for TPR; P use efficiency indices increased with increasing application rates. Bolland (2007) reported that low rate of PR application increased the dissolution of rock phosphate and hence its effectiveness. At low rate of TPR application, each rock phosphate particle will dissolve to its maximum extent in the soil due to the fact that the particles are farther apart. According to Huissen (2009), increasing rate of phosphorus application was found to decrease RAE. In contrast, Hongqing *et al.* (2001) reported that RAE generally increased with increasing P level.

The higher TPR partial factor productivity (PFP) observed in contour ridge plot in both seasons compared to the hoe tillage means that dry matter produced with a unit of P absorbed was higher in CR compared to that of the HT. This was possibly due to the disturbance of the soil under CR tillage leading to improvement in P availability and use efficiency by maize. Also, the soil moisture content recorded under CR plot was higher than that of HT.

The direct application of phosphate rock as P fertilizer has been found to compete favorably well with water soluble P fertilizers (Adediran *et al.*, 1998; Akande *et al.*,

1998). The relatively higher RAE values (88 % to 64 % with CR and 73 % to 50 % with HT) obtained in this study can be attributed to acidity of the soil which promoted the solubilization of the TPR. A similar result in Mali was reported by Hellums and Honolu (1992) who found that

Tilemsi phosphate rock was 78 to 100 % as effective as TSP during a 4-year study involving maize/cotton rotation.

5.2.7 Effects of tillage practices and soil amendments on value cost ratio (maize)

It is reported that any treatment with a VCR greater than 2 is profitable. Heerink (2005) stated that technically, VCR greater than 2 would imply profitability of fertilizer as long as other inputs were not altered as the use of fertilizer. Among the soil amendments, DAP applied at higher rate gave the best profitability in both seasons and for the two tillage options as indicated by its VCR (Table 4.22). The VCR value of TPR amended plots was higher than 2 indicating that the use of TPR as substitute for WSP can be a cheaper alternative for crop production in Sahel zone of Mali.

The use of CR showed higher VCR values than HT. In Mali, making of CR is not expensive as it is done with animal traction. The removal of grass before planting for HT is the same cost as the making of CR for farmers. The CR increased crop yield and consequently increased the benefit of crop cultivation.

5.3 Study 3: Assessment of the effects of different forms of Tilemsi phosphate rock on sorghum growth and yield and soil chemical properties

5.3.1 Effect of soil amendments on sorghum grain and biomass yields

Traditionally, sorghum has been known for being nutrient-use efficient and managed with low fertilizer rates, but yields can be increased with higher fertilizer application rates (Maranville *et al.*, 1980).

The P+SAM and P+K+SAM treatments produced the highest biomass and grain yields during the two growing seasons (Table 4.23). The increase in grain and biomass yields over the control was due to addition of fertilizer to the less fertile soil. The combined effect of major elements such as nitrogen, phosphorus, potassium enhanced the grain yields in the two treatments.

In the control plots, the plants had to use the limited nutrients that the soil could supply without any external inputs and hence the lowest yield. Wortmann *et al.* (2007) observed an increase in sorghum biomass and grain production by added N and P fertilizers. The relatively higher yield recorded under P+SAM treatment compared to sole application of TPR as pellet and P+K was due to the fact that the combined TPR with nitrogen fertilizer might have released nutrients faster than the sole application and hence improved nutrient uptake by the crop. According to FAO (2004), increased effectiveness of PR when applied as a dry mixture can be ascribed to the root-priming effect of soluble P and, therefore, increased root exploitation of the PR added. The relatively higher grain yield under P+SAM than P+K+SAM may be attributed to the higher sulphate of ammonia content of the former than the latter. Sulphate of ammonia is a physiologically acid N fertilizer that

when added to the TPR could enhance its dissolution. The higher the amount of sulphate of ammonia added, the greater the likelihood of dissolution of PR.

The non significant difference observed between sole application of TPR and TPR+KCl (P+K) on sorghum grain yield compared to the control in 2014, could be explained by the relatively low impact of KCl on the effectiveness of TPR. Mnkeni *et al.* (2000) showed that Panda PR was ineffective when applied alone but the mixture of Panda PR and triple super phosphate (TSP) or its compacted product increased wheat, maize, and soybean yields and P uptake significantly.

Several studies have reported the added benefit of mixing PR with organic amendments on soil properties and consequently on various crop growth and yield parameters. Okande *et al.* (2011) showed that application of Ogun rock phosphate (ORP) as a source of P, with or without organic amendments improved the growth and seed yield of kenaf. However, amending the OPR with various organic wastes and urea gave comparable growth and seed yields with NPK application (Okande *et al.*, 2011).

In this study, the mixture of TPR application with SAM (Sulphate of Ammonia) and K was found to give an increase of sorghum grain yield up to 70 % over the control. A similar result was obtained by Shahandeh *et al.* (2004) who reported an increase in millet yield by up to 89 % with TPR compared to the control. Bollan *et al.* (1990) reported that incorporation of PR ensures a steady supply of P over a long period and also provides a high rooting density to crops.

The grain yield significantly ($P < 0.001$) and positively correlated with soil available P ($r = 0.72$ and 0.56) and soil exchangeable bases (Ca, K, Mg) and total N in both seasons. Multiple regression analysis showed that available P significantly increased sorghum grain in 2013 compared to other soil properties. This result is in close agreement with

those reported by Teng and Timmer (1994). Mokuwunye *et al.* (1996) reported that P deficiency is the main biophysical constraints to food production in large areas of farmlands in sub-humid and semi-arid Africa. Phosphorus stimulates early growth root formation and the ability of plant to absorb water and other nutrients (Schachtman *et al.*, 1998). The low grain yield observed in 2013 can be explained by relatively low amount of rainfall and the frequent dry spell (Appendix 6) observed at the critical stage of sorghum growth in the first year of experimentation.

5.3.2 Effect of soil amendments on selected soil chemical properties

5.3.2.1 Soil pH

Soil pH is the deciding factor for availability of plant nutrients (Rahman and Ranamukhaarachi, 2003). It affects both phosphate adsorption and desorption and its availability for crop. The pH of the soil at the start of the experiment was strongly acid (4.15). The increase in soil pH was more pronounced with TPR amendment especially in the second year of experimentation than the no amendment plot and the initial value due to self liming effect of TPR. These results on pH confirm the findings of Zin *et al.* (2005) that PR fertilizers have Ca content (ranging from 24-33%) which could increase soil pH and effective cation exchange capacity (ECEC) with positive effect on crop growth and yield.

5.3.2.2 Total nitrogen

The soil total N was not significantly affected by soil amendments in 2013 (Table 4.24).

In the second year of experiment, significant differences were observed among amendments. The highest N level observed under P+SAM amendment was due to its higher N content than the other amendments.

Increase in P application rate increased the rate of N added to the soil particularly for the treatments P+SAM and P+K+SAM.

5.3.2.3 Available phosphorus

The values of available P recorded in this study were significantly influenced by soil amendments during the two years of experimentation (Tables 4.24 and 4.25). The increase in available P level over both the initial level and the value recorded under sole application of TPR and P+K compared to TRP amendment mixed with sulphate of ammonia in the first year was expected. The use of acidifying fertilizers has been shown to improve the effectiveness of PR (Peryea and Burrows, 1999). Sulphate of ammonia apart from supplying the important N and S nutrients acidifies the soil, hence creating conducive environment for PR dissolution (Prochnow *et al.*, 2006; Rivaie *et al.*, 2008). Mowo (2000) reported that the supply of plant nutrients improves crop growth, creating a P concentration gradient through increased P demand. The consequence of this is increase in PR dissolution. This may explain also the higher rate of available phosphorus observed under P+SAM and P+K+SAM compared to the control in both seasons. There was a significant difference in soil available phosphorus under TPR amendment at both P applied at 11 and 16 kg ha⁻¹ when compared with the control. Available phosphorus in the soil increased consistently with increased rate of TPR application due to the supply of more phosphorus to soil when the rate of TPR application increased.

5.3.2.4 Exchangeable cations

Soil amendments significantly ($P < 0.001$) influenced the exchangeable Ca in both seasons with the TPR plots recording higher value than no amendment plot (Tables 4.26 and 4.27).

This could be explained by the release of Ca in soil solution following the dissolution of TPR. This result is in close agreement with the results of Wright *et al.*

(1991) who observed a great increase soil solution Ca following the application of North Carolina Phosphate Rock (NCPR).

Similarly, increase in the rate of TPR application was found to increase the soil exchangeable Ca. This can be explained by the fact that high rate of TPR application enhanced soil Ca status by supplying more CaCO_3 . The mixture of sulphate of ammonium with TPR increased the solubility of TPR which eventually enhanced the level of dissolution product from phosphate rock in the soil. This is evidenced by the high rate of exchangeable Ca recorded under the combination of TPR and sulphate of ammonia.

The higher values recorded in the second year compared to the first year especially with TPR amendment can be explained by continual dissolution effect of TPR. Similar observation in incubation study with different sources of PR was made by Akande (2011) who observed an increase in Ca consistently over time. The trend observed with exchangeable Ca was similar to exchangeable Mg. Increasing the rate of TPR application consequently increased the level of exchangeable Mg in the two years.

Soil amendements influenced the soil exchangeable potassium in both seasons. P+K+SAM, P+K and P+SAM produced significantly higher values than the control due to their potassium contents.

5.3.2.5 Effective cation exchange capacity

The low ECEC recorded in the first year of the experiment (Table 4.26) compared to the initial value may be explained by the slow release of exchangeable bases especially Ca and Mg in soil solution in the short term. However, in 2014 the values of ECEC were high compared to the 2013 and the initial values. This could be explained by the release of basic cations with time upon dissolution of TPR. The high Ca and Mg contents in TPR and possibly decomposition of root biomass are mainly responsible for the increased exchangeable basic cations and, consequently, soil ECEC.

The combined application of sulphate of ammonia with TPR increased the solubility of TPR which consequently, enhanced the level of dissolution product from phosphate rock in the soil. This explained the relatively higher rate of ECEC recorded under the combined treatment of TPR and sulphate of ammonium in both seasons.

5.3.3 Effect of soil amendments on nutrient uptake (phosphorus and nitrogen)

Phosphorus uptake was enhanced with the combination of several nutrients than the sole application and no fertilizer use (Table 4.28). The highest P uptake in biomass and grain was recorded under TPR combined with sulphate of ammonia in both seasons. This may be attributed to the synergistic effects of N and P which increased absorption of P by plants due to better root growth with additional nitrogen supply through the different fertilizer TPR and $(\text{NH}_4)_2\text{SO}_4$ (Teng and Timmer, 1994).

Higher dose of P-application to sorghum in P+SAM and P+K+SAM produced significant increase in P-uptake over the control. The increase in P uptake with increasing levels of P can be explained by the supply of more of the nutrient in soil solution.

Correlation analysis between sorghum grain yield and available P indicated a strong relationship (Table 4.30). It was evident that higher uptake of the nutrients especially P in P +SAM and P+K+SAM at both 11 and 16 kg ha⁻¹ by the crop contributed towards the increased grain yield, which was not observed in the un-amended plot.

The trend observed for N uptake was almost similar to that of P uptake except that in the decreasing order of N uptake, the treatment P+SAM performed better than P+K+SAM in both seasons for grain and biomass N uptake. This can be explained by the high level of sulphate of ammonia mixed with TPR for P+SAM fertilizer than P+K+SAM fertilizer. The N uptake increased by the different P amendments compared to the control, and significant difference was observed between P+SAM, P+K+SAM at higher rate compared to the remaining rates in both seasons. The different levels of nitrogen in the different fertilizers influenced the level of N in soil solution and may explain the difference in N uptake recorded in both years.

5.3.4 Relationship between available P crop growth parameters and some soil properties

Soil available P was strongly ($P < 0.001$) correlated with sorghum growth rate, grain and biomass N uptake, total N uptake and soil ECEC in both seasons. The multiple regression analysis showed that sorghum growth at earlier stage (C1) and total N uptake have significant impact on soil available P in both seasons than the other parameters (Tables 4.34 and 4.35).

The significant impact of sorghum growth at earlier stage (C1) in both seasons on soil available P, indicated that the increase in soil available P from TPR is more related to overall growth of crop which had a good impact on P uptake than the acidity generated by

nitrogen fertilizer in the study site. The impact of nitrogen fertilizer on phosphorus absorption by sorghum is more important at the earlier stage of crop growth. Incorporation of $(\text{NH}_4)_2\text{SO}_4$ with TPR at sowing can be the best way to increase TPR solubility and P availability.

5.3.5 Phosphorus use efficiency

Nutrient use efficiency is the ability of a plant to utilize soil available nutrients to result in measurable yield or yield parameters such as plant height, leaf development, dry matter and fruit / grain production (Hati *et al.*, 2006). Among TPR amendments, the highest efficiency was observed with P+SAM amendment compared to others. This may be attributed to the direct effect of the high nitrogen content which improves crop growth. The combination of $(\text{NH}_4)_2(\text{SO}_4)$ with TPR led to an increase in uptake of P hence the highest P use efficiency obtained.

In the case of PRE, P+K+SAM recorded high P recovery in 2014 than the other treatments and this was probably due to the synergistic effect of the three major elements N, P, K in this amendment.

5.3.6 Effect of soil amendments on soil phosphorus partial balance

Negative balance observed in this study with no P application (Table 4.38) was expected because of the low initial soil fertility. The negative P balance suggests that sorghum production in both seasons relied on soil P stocks to sustain crop production. Following the application of the P amendments, positive balances were found in TPR amended plots in both seasons and with both rates of phosphorus applied. The highest value was recorded under the 16 kg ha^{-1} P application. This was due to the substantial amount of P added at higher rate than at lower rate. Higher positive balance was recorded under sole application

of TPR and TPR associated with potassium than TPR with nitrogen fertilizer. This could be explained by the higher phosphorus uptake and phosphorus recovery with TPR associated with nitrogen fertilizer. The Decrease in P balance with time could be attributed to the high P uptake and high grain and biomass yields recorded during the second year of the experiment than in the first year.

5.3.7 Value cost ratio

It is reported that any treatment with a VCR greater than 2 is profitable. VCR greater than 2 would imply profitability of fertilizer use. Among the soil amendments, the P+SAM treatment gave the best profitability in 2013 while the sole application of Pellet at 16 kg ha⁻¹ had a highest profitability in 2014 (Table 4.39). The VCR for the other soil amendments was lower than those for sole amendment of TPR in pellet form because the prices were higher.

The lowest VCR was recorded with treatment P+K (TPR mixing with KCl). This was due to the addition of KCl which had no much impact on phosphorus availability from TPR compared to sulphate of ammonia, and hence its impact on sorghum productivity was less compared to the combination of TPR with sulphate of ammonia. Moreover combining TPR with KCl is more costly compared to the sole application of TPR as pellet.

CHAPTER SIX

6.0 SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary and conclusion

Many soils in Mali are characterized by deficiency of plant-available P. The use of water soluble phosphate is not a common practice to address this problem due to its high cost. The main purpose of this research was therefore to develop strategies based on the use of TPR as an alternative to WSP for sustainable crop production, thereby increasing the productivity of cropping systems.

On the basis of the outcomes of this present study, the following conclusions were drawn:

- (i) The phosphorus sorption maxima and standard phosphorus requirement varied widely among the four soils studied and were influenced by the available phosphorus content of the soils but were much linked to the soil clay content. The adsorption of P was a dominant mechanism in the phosphorus retention process, despite the low clay content of the different soils. The P requirement of the soils studied ranged between 16 and 53.76 kg ha⁻¹ and was mainly related to soil texture. Hence soils with high levels of clay required more P than those with low clay content. The values of P required to attain 0.2 mg L⁻¹ in soil solution were high compared to TPR recommended rate in Mali for all the soils under study. The study has demonstrated that phosphate sorption isotherm method can be used to predict standard phosphorus requirement (SPR) in the sandy soils of Mali based on the use of TPR.
- (ii) Contour ridge (CR) tillage had positive impact on P availability from TPR, due to adequate soil moisture conservation. However, soil moisture was not a driving factor on P availability from TPR but a proxy that enhanced P uptake and crop growth, reducing

P concentration in soil solution which improved TPR solubility. This finding has confirmed that TPR used under CR tillage in the Sahel can be almost as effective as water soluble phosphate like DAP under low and erratic rainfall with annual rainfall (between 500 to 600 mm). Tilemsi phosphate rock can therefore be used as alternative to WSP in the Sahelian area of Mali.

(iii) The combination of TPR with sulphate of ammonia increased the solubility of TPR. The increase in soil available P was linearly related to the amount of sulphate of ammonia added to TPR. The increase in solubility of combined application of TPR and sulphate of ammonia, seemed more linked to the supply of important N and S nutrients that improved crop growth and hence P uptake which in return improved TPR solubilization, rather than the acidifying effect of sulphate of ammonia. The effect of sulphate of ammonia on TPR solubility and crop growth and yield seemed crucial at the earlier stages of crop growth. The efficiency of combining sulphate of ammonia and TPR increased with increased rate of TPR application.

In low and infertile soils, combined application of TPR and sulphate of ammonia even at low rate can be an alternative for the use of water soluble phosphorus, since this combination improved the overall crop growth and yield compared to the control. The results have confirmed the hypothesis of this study that combining TPR with sulphate of ammonia will enhance phosphorus availability under field conditions.

The impact of TPR on crop growth and yield as well as the overall soil chemical properties improved with one time application of TPR at 16 kg ha^{-1} . The annual application of TPR seemed more beneficial as it allowed steady supply of available P for crop growth and did not add more Ca in soil solution which could have increased pH of the soil with low

buffering capacity as well as impeded P release from TPR. This indicates that the soils of the study site need only the addition of required amount of P (16 kg ha^{-1}) in phosphorus fertilizer than the application of huge rate at once.

In both Tilemsi phosphate rock used under different tillage practices and combined with sulphate of ammonia, phosphorus applied at 16 kg ha^{-1} was found to increase soil available P for the different P types used. Also, it improved crop growth and yield and phosphorus uptake, confirming that P applied at 16 kg ha^{-1} is an optimum rate of P application.

The use of contour ridge technique improved TPR use efficiency compared to HT can therefore help farmers increase profitability. Furthermore, mixing TPR with $(\text{NH}_4)_2\text{SO}_4$ enhanced TPR effectiveness which was proportional to the rate of $(\text{NH}_4)_2\text{SO}_4$ used which was not obtained with the combined application of TPR with KCl or sole TPR.

6.2 RECOMMENDATIONS

This study has provided evidence that direct use of TPR could be an alternative to the application of WSP to enhance soil P availability and crop growth and yield. However, further research is required to assess the impact of standard phosphorus requirement (P SPR) for soils from Longorola, Danga and Niessoumana under field conditions. Future

assessment is needed to provide an understanding on the behavior of crop roots under combined use of TPR with sulphate of ammonia at different rates and also under different tillage practices. There is a need to establish the appropriate rates of the combination of sulphate of ammonia with TPR for direct use in laboratory and field trials.

The logo of KNUST (Kenya National University of Science and Technology) is centered in the background. It features a yellow eagle with spread wings perched on a green shield. Above the eagle is a black mortar and pestle with a red flame. The entire emblem is set against a light grey background with the word 'KNUST' in large, semi-transparent letters.

REFERENCES

Aaroon, S. T., Josepha, N., Foba, T., Susan, Y., Yakum, N. and Frederic, T. (2013).

Phosphorus fixing capacity of a volcanic soil on the slope of mount Cameroon.

Agriculture and Biology Journal of North America 4(3): 166 - 174.

Adediran, J.A., Oguntoyinbo, F.I., Omonode, R. and Sobulo, R.A. (1998).

Agronomic evaluation of phosphorus fertilizers developed from Sokoto Rock Phosphate in Nigeria. Comm. Soil Sci. Plant Anal 29: 2659 - 2673.

- Agbenin, J.O. and Igbokwe, S.O. (2006).** Effect of soil– dung manure incubation on the solubility and retention of applied phosphate by a weathered tropical semiarid soil. *Geoderma* 133: 191 - 203.
- Akande, M.O. (2011).** Effect of phosphate rock on selected chemical properties and nutrient uptake of maize and cowpea grown sequentially on three soil types in south western Nigeria. *International Research Journal of Agricultural Science and Soil Science* 11: 471- 480.
- Akande, M.O., Aduayi, E.A., Olayinka, A. and Sobulo, R.A. (1998).** Efficiency of Sokoto rock phosphate as a fertilizer source for maize production in South Western Nigeria. *Journal of Plant Nutrition* 21: 1339 – 1353.
- Allen, V.B. and David, J.P. (2007).** *Handbook of Plant Nutrition*, 632p. CRC Press.
- Anderson, J.M. and Ingram, J.S.I. (1993).** *Tropical Soil Biology and Fertility: A Handbook of Methods*, second ed. CAB International, Wallingford, Oxon, England, 221 pp.
- Arai, Y. and Sparks, D.L. (2007).** Phosphate reaction dynamics in soils and soil minerals: a multi scale approach. *Adv Agron* 94: 135 – 179
- Bationo, A. and Mkwunye, A.U. (1991).** Alleviating soil fertility constraints to increased crop production in West Africa: The experience in the Sahel. *Fert. Res* 29: 95 - 115.
- Bationo, A., Rhodes, E., Smaling, E.M.A. and Visker, C. (1996).** Technologies for restoring soil fertility. In A.U. Mkwunye., A. de Jager., and E.M.A. Smaling. (eds). *Restoring and maintaining the productivity of West African soils: key to sustainable development Misc. Fert. Stud. 14. Int. Fert. Dev. Ctr., Africa, Lome, Togo*

- Batjes, N.H. (2011).** Global distribution of soil phosphorus retention potential. Wageningen, ISRIC- World Soil Information.
- Blanco-Canqui, H. and Lal, R. (2008).** No-tillage and soil-profile carbon sequestration: An on-farm assessment. *Soil Science Society of America Journal* 72 (3): 693 - 701.
- Bollan, N.S. and Hedley, M.J. (1990).** Dissolution of phosphate rocks in soils. 2. Effect of pH on the dissolution and plant availability of phosphate rock in soil with pH dependent charge. *Fert. Res* 24: 125 - 134.
- Bollan, N.S., White, R.E. and Hedley, M.J. (1990).** A review of the use of phosphate rocks as fertilizers for direct application in Australia and New Zealand. *Aust. J. Exp. Agric* 30: 297 – 313.
- Bollan, N. S. and Duraisamy, V. P. (2003).** Role of inorganic and organic soil amendments on immobilization and phyto-availability of heavy metals: a review involving specific case studies. *Aust. J. Soil Res.* 41: 533 - 556
- Bolland, M. (2007).** Effectiveness of rock phosphate. Department of Agriculture and Food Government of Western Australia. Farm note 33/96 Note: 215.
- Bollan, M.D.A. and Gilkes, R.J. (1989).** Reactive rock phosphate fertilizers and soil testing for phosphorus: The effect of particle size of the rock phosphate. *Fertilizer Research* 21: 75- 93- Kluwer Academic Publishers.
- Bollan, M.D.A. and Gilkes, R.J. (1997).** The agronomic effectiveness of reactive phosphate rocks 2. Effect of phosphate rock reactivity. *Australian Journal of Experimental Agriculture* 37: 937 - 946
- Brady, N.C. and Weil, R.R. (1996).** The nature and properties of soils. 11th edition. New Jersey. United Kingdom: Prentice Hall International, 740 p

Chien , S.H. and Friesen, D.K. (1992). Phosphate rock for direct Application.

Workshop on future direction for agricultural phosphorus research pp.47 – 52

Tennessee valley authority. Muscle Shoals Alabama. U.S.A

Chien, S. H., Hammond, L. L. and Leon, L. A. (1987). Long-term reactions of phosphate rocks with an oxisol in Colombia. Soil Sci 144 : 257 – 265.

Chien, S.H. (1977). Dissolution of phosphate rocks in a flooded acid soil. Soil Sci. Soc. Am. J 41: 1106 - 1109.

Chien, S.H. (1993). Solubility assessment for fertilizer containing phosphate rock. Fert. Res., 35: 93-99

Chien, S.H. (2003). Factors affecting the agronomic effectiveness of phosphate rock for direct application. In S.H. Chien., L.I. Prochnov., R. Mikkelsen. (eds). Agronomic use of phosphate rock for direct application. Better Crops/Vol.94 No.4

Chien, S.H. and Menon, R.G. (1995). Factors affecting the agronomic effectiveness of phosphate rock for direct application. Fert. Res 41: 227 – 234

Chien, S.H., Menon, R.G. and Billingham, K.S. (1996). Phosphorus availability from phosphate rock as enhanced by water-soluble phosphorus. Soil Sci. Soc. Am. J., 60: 1173 – 1177.

Chien, S.H., Prochnov, L.I., Tu, S. and Synder, C.S. (2010). Agronomic and environmental aspects of phosphate fertilizers varying in source and solubility: an update. Nutr Cycl Agroecosyst 89: 229 - 255

Crosson, P. and Anderson, J.R. (1995). Achieving a sustainable agricultural system in sub-Saharan Africa. Building blocks for Africa 2025. Pap. 2. World Bank, Washington, DC.

Cornforth, I.S. (2012). The fate of phosphate fertilizers in soil. <http://>

Nzic.org.nz/Chem Processes/Soils/2D.Pdf. Department of Soil Science, Lincoln University.

Accessed Feb 2012.

Commissariat a la securite alimentaire (CSA). (2007). Gouvernement du Mali. Plan de sécurité alimentaire commune rurale de Konobougou. 17 pp

De Angelis, K.M. (2007). Measurement of soil moisture content by gravimetric water method. In C.A. Black. (eds). "Methods of Soil Analysis: Part I physical and mineralogical properties". American Society of Agronomy, Madison, Wisconsin, USA.

Debrah, S.K. (2000). La place du phosphate naturel de Tilemsi dans l'initiative pour la fertilité des sols au Mali. Rapport provisoire. IFAD-International Fund for Agricultural Development Afrique, Togo. 20 pp.

Devau, N., Le Cadre, E., Hinsinger, P. and Gerard, F. (2010). A mechanistic model for understanding root-induced chemical changes controlling phosphorus availability. Ann Bot (Lond) 105: 1183 – 1197.

De Vries, J. and Toenniessen, G. (2001). Securing the harvest: biotechnology, breeding and seed system for African crops. CAB International, Wallingford, UK. pp 208.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F. and Cohan, J. P. (2014). Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agriculture, Ecosystems & Environment 188: 134 - 146.

Dobermann, A. (2005). Nitrogen Use Efficiency. State of the art. IFA international workshop on enhanced - efficiency fertilizers, Frankfurt Germany, June 28-30

Dodor, D.E. and Oya, K. (2000). Phosphate sorption characteristics of major soils in

Okinawa, Japan. Commun. Soil Sci. Plant. Anal 31: 277 - 288.

Doumbia, M., Ansumana, J., Modou, S., Traore, K., Russell, Y., Richard, K., Kevin, B., Berthe, A., Charle, Y., Antonio, Q., Pierre, C.S. and Traore, A. B. (2008). Sequestration of organic carbon in West African soils by aménagement en courbes de niveau. Agron. Sustain. Dev. INRA, EDP Sciences, and DOI: 10.1051/agro: 041

Doumbia, M.D. (1990). Acid soil fertility at the Cinzana station, Mali (West Africa), M.S. thesis. soil and crop sci. Dept., Texas A&M Univ., College Station, TX. **Erich, M.S., Fitzgerald, C.B. and Porter, G.A. (2002).** The effect of organic amendments on phosphorus chemistry in a potato cropping system. Agriculture, Ecosystems and Environment 88: 79 - 88

Fageria, N. K., Dos Santos, A. B. and Moraes, M. F. (2010). Influence of urea and ammonium sulfate on soil acidity indices in lowland rice production.

Communications in Soil Science and Plant Analysis 41: 1565 – 1575

FAO. (2004). Use of rocks phosphate for sustainable agriculture. FAO Fertilizer and Plant Nutrition Bulletin 13. ISSN 0532-0488

FAO. (2014). Machinery, tools and equipment. Agriculture and consumer protection department. Conservation agriculture. [http: www.FAO.org/ag/ca](http://www.FAO.org/ag/ca). Accessed March 2015.

Fatondji, D. (2002). Organic amendment decomposition, nutrient release and nutrient uptake by millet in a traditional land rehabilitation technique (Zai) in the Sahel. Ecology and Development Series. PhD. Dissertation, University of Bonn. Bonn, Germany. pp 147.

- Flach, E.N., Quak, W. and Van Diest, A. (1987).** A comparison of the rock phosphate-mobilizing capacities of various crop species. *Trop. Agric* 64: 347-352.
- Fox, R. L. (1992).** Predicting plant nutrient requirements—A rational approach. Proceedings of the International symposium nutrient management for sustained Productivity, Department of Soils, Punjab Agricultural University. Ludhiana, pp, 43–54.
- Fox, R.L. (1981).** External phosphorus requirements of crops. Chap 12. PP 223-233. *Chemistry in soil environment WISC: Soil Science Society of America.*
- Furhata, T., Suzuki, M. and Sakurai, H. (1992).** Kinetic characterization of two phosphate uptake systems with different affinities in suspension-cultured *Catharanthus roseus* protoplasts. *Plant Cell Physiol* 33: 1151 – 1157.
- Gardener, F.P., Pearce, R.B. and Mitchell, R.L. (1985).** *Physiology of Plants*, pp 187-2008. Iowa State University Press
- Gholizadeh, A., Ardolan, M., Tehrani, M.M., Hosseini, H.M. and Karimian, N. (2009).** Solubility test in some phosphate rocks and their potential for direct application in soil. *World Applied Sciences Journal* 6 (2): 182 - 190.
- Ghosal, P.K. and Chakraborty, T. (2012).** Comparative solubility study of four phosphatic fertilizers in different solvents and the effect of soil. *Resources and Environment* 2(4): 175 - 179.
- Gichangi, E.M. and Mnkeni, P.N.S. (2009).** Effects of goat manure and lime addition on phosphate sorption by two soils from the Transkei Region, South Africa. *Commun. Soil Sci. Plan. Anal* 40 (21-22): 3335 - 3347.
- Gichangi, E.M., Mnkeni, P.N.S. and Muchaonyerwa, P. (2008).** Determination of the external phosphate requirements of two South African soils in a glasshouse pot experiment. *Tropical and Subtropical Agroecosystems* 8: 243 – 250

Gigou, J., Traoré, K., Giraudy, F., Coulibaly, H., Sogoba, B. and Doumbia, M. (2006).

Aménagement paysan des terres et réduction du ruissellement dans les savanes africaines. In *Agricultures* 15(1): 116-122.

Gillard, G., Sale, P.W.G. and Tennakoon, S.B. (1997). Building an expert system to advise on the use of the reactive phosphate rock on Australian Pastures. *Australian Journal of Experimental Agriculture* 37: 1077 - 1084.

Hammond, L.L., Chien, S.H. and Mokwunye, A.U. (1986). Agronomic evaluation of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. *Adv. Agron* 40: 89 - 140.

Hanafi, M. M., Syers, J. K. and Bollan, N. S. (1992). Leaching effect on the dissolution of two phosphate rocks in acid soils. *Soil Soc. Am. J* 56: 1325 - 1330

Harrison, A.F. (1987). Soil Organic Phosphorus—A Review of World Literature. CAB International, Wallingford, Oxon, UK, pp 257

Hati, K.M., Mandal, K.G., Misra, A.K., Ghosh, P.K. and Bandyopadhyay, K.K. (2006). Effect of inorganic fertilizer and farmyard manure on soil physical properties, root distribution, and water-use efficiency of soybean in Vertisols of central India. *Bioresource Technology* 97(2): 2182 - 2188.

Havlin, J.L., Beaton, J.D., Tisdale, S.L. and Nelson, W.L. (2005). Soil fertility and fertilizers: An introduction to Nutrient Management 7th Ed. Pearson Education Inc. 515p, Upper Saddle River, New Jersey.

Haynes, R. J. and Mokolobate, M. S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in*

Agroecosystems 59: 47 - 63.

Hedley, M.J. and Bollan, N.S. (1997). Developments in some aspects of reactive phosphate rock research and use in New Zealand. *Aus. J. Exp. Agric.*, 37: 861–884.

Heerink, N. (2005). Soil fertility decline and economic policy reform in Sub Saharan. *Land use policy*. 22: 67 - 74

Hellums, D.T. and Honolu, (1992). Alternative phosphorus fertilizers in the tropics: “An agronomic and economic evaluation” Phosphorus Decision Support System Workshop (BALAS, S., ed), *Trop Soils Bulletin* No. 92- 01.

Hellums, D.T., Chien, S.H. and Touchton, J.T. (1989). Potential agronomic value of calcium in some phosphate rocks from South America and West Africa. *Soil Sci. Soc. Am. J* 53: 459 - 462.

Henaio, J. and Baanante, C.A. (1999). An evaluation of strategies to use indigenous and imported sources of phosphorus to improve soil fertility and land productivity in Mali. International Fertilizer Development Center IFDC. P.O.Box 2040 Muscle Shoals, Alabama 35662 (U.S.A.)

Henry, P. C. and Smith, M. F. (2003). A single point sorption test for the routine determination of the phosphorus requirement of low to moderate P-fixing soils; *South Africa Journal of Plant and Soil* 20: 132 – 140.

Hong-Qing, H., Yuan, L. X., FU.L.J ., Lin, X., Jung,L., Fan, L. (1996). The effect of direct application of phosphate rock on increasing crop yield and improving properties of red soil. *Nutrient Cycling in Agroecosystems* 3 (46): 235 - 239.

Hongqing, H., Chunying.T., Chongfa, C., Jizheng, H. and Xueyuan.L.(2001).

Availability and residual effects of phosphate rocks and inorganic P fractionation in a red soil of Central China. *Nutrient Cycling in Agro ecosystems* 59: 251-258.

Hu, H.Q., Li, X.Y., Liu, J.F. and Xu, L. (1997). The effect of direct application of phosphate rock on increasing crop yield and improving properties of red soil. *Nutr. Cycl. Agroecosys* 46: 235 – 239

Hua, Q., Li, J. and Zhou, J. (2008). Enhancement of phosphorus solubility by humic substances in Ferrasols. *Pedosphere*. 18(4): 533 - 538.

Hue, N. V. and Fox, R. L. (2010). Predicting plant phosphorus requirements for Hawaii soils using a combination of phosphorus sorption isotherms and chemical extraction methods *communications in Soil Science and Plant Analysis* 41:133 – 143.

Hue, N. V., Ikawa, H. and Huang , X. (2000). Predicting soil phosphorus requirements. In N. V. Hue., R. L. Fox. (eds). *Predicting plant phosphorus requirements for Hawaii soils using a combination of phosphorus sorption isotherms and chemical extraction methods Communications in Soil Science and Plant Analysis* 41: 133 – 143.

Huissen, A.H.A. (2009). Phosphorus use efficiency by two varieties of corn at different phosphorus fertilizer application rates. *Research Journal of Applied Sciences* 4: 85 - 93.

IFDC. (2010). World phosphate rock reserves and resources. IFDC P.O. Box Muscle Shoals, Alabama 35662, USA Iowa State University Press.

Iyamuremye, F. and Dick, R.P. (1996). Organic amendments and phosphorus sorption. *Adv. Agronomy* 56: 139 - 185.

- Iyamuremye, F., Dick, R.P. and Baham, J. (1996).** Organic amendments and phosphorus dynamics: 1. Phosphorus chemistry and sorption Soil Sci 161: 426–435
- Jing, J.Y., Rui, Y.K., Zhang, F.S., Rengel, Z. and Shen, J.B. (2010).** Localized application of phosphorus and ammonium improves growth of maize seedlings by stimulating root proliferation and rhizosphere acidification. Field Crops Res 119: 355 – 364
- Johnston, A.E. (2000).** Soil and plant phosphate. International Fertilizer Industry Association, Paris, France.
- Jones Jr, J. B., Wolf, B., Mills, H. A. (1991).** Plant analysis handbook. In N. V. Hue., R. L. Fox. (eds). Predicting plant phosphorus requirements for Hawaii soils using a combination of phosphorus sorption isotherms and chemical extraction methods communications in soil science and Plant Analysis 41: 133 – 143.
- Juo, A.S., Franzeluebbers, R.K., Dibiri, A. and Ikhile, B. (1996).** Soil properties and crop performance on a kaolinitic alfisol after 15 years of fallow and continuous cultivation. Plant and Soil 180 (2): 209 - 217.
- Kablan, R., Yost, R.S., Brannan, K., Doumbia, M.D., Traoré, K., Yoroté, A., Toloba, Y., Sissoko, S., Samaké, O., Vaksman, M., Dioni, L. and Sissoko, M. (2008).** Aménagement en courbes de niveau “Increasing rainfall capture, storage, and drainage in soils of Mali”, Arid Land Research and Management 22 (1): 62 – 80.
- Kaleeswari, R.K. and Subramanian, S. (2001).** Chemical reactivity of phosphate rocks - a review. *agric. rev* 22 (2): 121 – 126.

- Kanabo, I.A.K. and Gilkes, R.J. (1987).** The influence of addition of goethite to soil on the dissolution of North Carolina phosphate rock .Australian Journal of Soil Research 25: 313 - 322.
- Kanwar, J.S and Grewal, J. (1990).** Phosphorus fixation in Indian soils. 2nd edition. New Delhi, India: Indian Council of Agricultural Research.
- Koenig, R.T., Barnhill, J.V. and Hurst, C.J. (2000).** Sampling depth effects on sodium bicarbonate (NaHCO_3)-extractable phosphorus and potassium and fertilizer recommendations. Commun. Soil Sci. Plant Anal 31: 375 - 386.
- Kouyaté. Z., Diallo. D., N'Diaye, K. and Ayemou, A. (2012).** Influence of crop management systems on soil properties and sorghum yields in the Sahelian zone of Mali. African Journal of Agricultural Research 7(37) : 5217 - 5223
- Landon, J.R. (1996).** Booker tropical soil manual. A handbook for soil survey and agricultural land evaluation in the tropics and sub-tropics. Longman. 431pp.
- Lindsay, W.L., Vlek, P.L.G. and Chien, S.H. (1989).** Phosphate minerals. In J.B. Dixon., S.B. Weed. (eds,) Minerals in Soil Environment, Ed 2. Soil Science Society of America, Madison, WI 22 : 1089 – 1130
- Manoharan, V., Loganatham, P. and Tillman, R.W. (1995).** Effects of long- term application of phosphate fertilizers on soil acidity under pasture in New Zealand. Developments in Plant and Soil Science 64: 85 - 91
- Maranville, J. W., Clark, R. B. and Ross, W. M. (1980).** Nitrogen efficiency in grain sorghum. J. Plant Nutr. 2: 577 – 589.
- Marschner, H. (1995).** Mineral nutrition of higher plants. 2nd ed Academic Press, London.
- Mclean, E.O. (1982).** Soil pH and lime requirement. Soil Sci. Soc. Amer. Proc. 3: 162 - 167

Mengel, K. (1986). Umsatz im Boden und Ertagswirkung rohphosphathaltiger
Düngemittel. Z. Pflanzenmähr. Bodenk 149 : 674 - 690.

Mengel, K., Kirkby, E.A., Kosegarten, H. and Appel, T. (2001). Principles of plant nutrition. 5th
ed. Kluwer Academic Publishers, Dordrecht, The Netherlands

Mnkeni, P.N.S., Chien, S.H. and Carmona, G. (2000). Effectiveness of Panda Hill
phosphate rock compacted with superphosphate as source of phosphorus for rape,
wheat, maize, and soybean. Comm. Soil Sci. Plant Anal 31: 3163 - 3175.

Mokwunye, A.U and Hammond, L. L. (1992). Myths and science of fertilizer use in the
tropics. Soil Science Society of America. Special Publication 29 : 121 – 134.

Mokwunye, A.U., De Jager, A. and Smaling, E.M.A. (1996). Restoring and
maintaining the productivity of West African soils: key to sustainable
development. IFDC-Africa, LEI-DLO and SC-DLO

Mowo , J.G. (2000). Effectiveness of phosphate rock on ferralsols in Tanzania and the
influence of within-field variability. PhD. Thesis, Department of environmental
science, sub-department of soil science and plant nutrition, Wageningen
University.

**Musa, I.M., Singh, A., Abubakar, L., Noma, S.S., Alhassan, J. and Haliru, B.S.
(2012).** Influence of Cultivar and Sokoto phosphate rock Levels on the yield and
yield components of groundnut (*Arachis hypogaea L.*) in dry Sub-Humid Sokoto
area, Nigeria. Nigerian J. of Basic and Applied Science 20 : 49 - 54.

Nathan, N. and Mikelsen, R. (2008). Meeting the phosphorus requirements on organic farms.
Better crops/ vol 92 Num 1.

- Naidu, R., Syers, J.K., Tillman, R.W. and Kirkman, J.H. (1990).** Effect of liming on phosphate soption by acid soils. J. Soil Sci. 41: 163 - 175.
- Nelson, D.W. and Sommer, L.E. (1982).** Total carbon, organic matter. Methods of soil Analysis, part 2. ASA 9.2 edition
- Nelson, D.W., and Sommers, L.E. (1980).** Total nitrogen analysis for soil and plant tissues.J.Asso. Official Anal. Chemist 63: 770 -778.
- Notholt, A.J.G. and Highley, D.E. (1986).** World phosphate resources, with particular reference to potential low-grade ores. Trans. Instn. Min. Metall. (Section B: Applied Earth Sci.) 95: 125 - 132.
- Okande, M.O., Makinde, E.A., Aluko. O.A., Oluwatoyinbo. F.I. and Adediran. J.A. (2011).** Rock phosphate amendment effect on kenaf (*Hibiscus cannabinus L.*) Growth and yield. Tropical and Subtropical Agroecosystems 14 (2) 559 - 565.
- Olsen, S.R. and Sommers, L.E. (1982).** Phosphorus. In A.L. Page. (eds) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Onwonga, R.N., Lelei, J.J. and Macharia, J.K. (2013).** Comparative effects of soil amendments on phosphorus use and agronomic efficiencies of two maize hybrids in acidic soils of Molo county, Kenya. American journal of Experimental Agriculture 3(4): 939 - 958.
- Ouattara, B. (1994).** Contribution à l'étude de l'évolution de propriétés physiques d'un sol ferrugineux tropical sous culture: pratiques culturelles et états structuraux du sol. Thèse UNCI, Abidjan, 153 pp.
- Papini, R., Castelli, F. and Panichi, A. (2000).** Phosphorus retention and leaching in some sandy soils of Northen Italy. Ital.J.Ag on 3(2): 101 - 107.

- Parr, J.F., Papendick, R.I., Hornick, S.B. and Meyer, R.E. (1990).** The use of cover crops, mulches and tillage for soil water conservation and weed control.
IBSRAM Proceedings No.10. Bangkok: IBSRAM. PP. 246-261.
- Pascal, M. and Traore, H. (1989).** Eocene Tilemsi phosphorite deposits, eastern Mali.
In P.V. Straaten (eds). Rocks for crops: agrominerals of sub-Saharan Africa. ICRAF, Nairobi, Kenya, 338 pp.
- Perrot, K.W. and Wise, R.G. (2000).** Determination of residual reactive phosphate rock in soil. *Com. Soil sci plant-anal* 31(11-14): 1809 - 1824
- Peryea, F.J. and Burrows, R.L. (1999).** Soil acidification caused by four commercial nitrogen fertilizer solutions and subsequent soil pH rebound. *Commun. Soil Sci. Plant Anal* 30 (3&4): 525 - 533.
- Pierzynski, G.M., Mc Dowell, R.W. and Sim, T.J. (2005).** Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In: N.H Batjes. (eds). Global distribution of soil phosphorus retention potential. Wageningen, ISRIC- World Soil Information.
- Prochnow, L. I., Quespe, J. F. S., Francisco, E. A. B. and Braga, G. (2006).** Effectiveness of phosphate fertilizers of different water solubilities in relation to soil phosphorus adsorption, *Scientia Agricola* 63: 333 - 340
- Raghothama, K.G. (1999.)** Phosphate acquisition. *Annu Rev Plant Physiol Plant Mol Biol* 50: 665 - 693.
- Raguram, S. M. and Ramachandra, C.V.M. (2014).** Direct Application of Phosphate Rock with ammonium sulphate or along with organic manure *IJALSE* 1 (1): 87-88.

- Rahman, M. M. and Ranamukhaarachchi, S. L. (2003).** Fertility status and possible environmental consequences of Tista floodplain soils. *Thammasat Int. J. Sc. Tech* 8 (3): 111 - 117.
- Rajan, S.S.S., Fox, R.L., Saunderson, W.M.H. and Updell, M.P. (1991).** Influence of pH, time and rate of application on phosphate rock dissolution and availability to pasture.II. Soil chemical studies. *Fertilizer Res* 28: 85 - 93.
- Rajan, S.S.S., Watkinson, J.H. and Sinclair, A.G. (1996).** Phosphate rock for direct application to soils. *Ad. Agron.* 57: 78 –159.
- Rhoades, J. D. (1982).** Cation exchange capacity. In A.L. Page. (ed.) *Methods of soil analysis*. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Riffaldi, R., Saviozzi, A., Levi-Minzi, R. and Menchetti, F. (1994).** Chemical characteristics of soil after forty years of continuous maize cultivation. *Agriculture, Ecosystems and Environment* 49 (3): 239 - 245.
- Rivaie, A., Loganathan, A. P., Graham, J. D., Tillman, R. W. and Payn, T. W. (2008).** Effect of phosphate rock and triple superphosphate on soil phosphorus fractions and their plant availability and downward movement in two volcanic ash soils under *Pinus radiata* plantations in New Zealand”, *Nutr Cycl Agroecosyst* (82) : 75 - 88.
- Roland, J. B., Pedro A. S. and Calhoun, F.(1997).** Replenishing soil fertility in Africa. SSSA. Special Publication. Number 51.
- Roth, G.W., Beegle, D. B., Heinbaugh, S.M. and Antle, M.E. (2006).** Starter fertilizers for Corn on soils testing high in phosphorus in the Northeastern USA. *Agron J* 98: 1121 - 1127
- Sale, P. W. G. and Mokwunye, A. U. (1993).** Use of phosphate rocks in the tropics.

Fertilizer Research 35: 33 - 45 Kluvert Academic Publishers.

Sample, E.C., Soper, R.J. and Racz, G.J. (1980). Reactions of phosphate fertilizers in soils.

Fertilizer Res 55: 90 - 95.

Sanchez, P.A., Palm, C.A. and Buol, S.W. (2003). Fertility capability soil

classification: a tool to help assess soil quality in the tropics. *Geoderma* 114: 157 - 185.

Sanginga, N. and Woomer, P.L. (2009). Integrated soil fertility management in

Africa: principles, practices and developmental process. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture.

Nairobi. 263 pp.

Schachtman, D.P., Reid, R.J. and Ayling, S.M. (1998). Phosphorus uptake by plants: From

soil to cell. *Plant physiology* 116: 447 - 453.

Sedogo, P.M., Bado, B.V., Hien, V. and Lompo, F. (1991). “ Utilisation efficace des

engrais azotes pour une augmentation de la production vivrière : L'expérience du

Burkina Faso. In A.U. Mokwunye. (ed). Alleviating Soil fertility constraints to

increased crop production in West Africa, 115 - 123 Kluvert Academic

Publishers.

Shahandeh, H., Hons, F. M., Hossner, L. R. and Doumbia, M. D. (2004). Effect of

Diamou Lime, Gypsum, and Tilemsi Phosphate Rock on Acid Soils of the

Sudano-Sahelian Region of Mali, *Arid Land Research and Management*. 18: 77-

88.

Sharif, M., Arif, M., Burni, T., Khan, F., Jan, B. and Khan, I. (2014). Growth and

phosphorus uptake of sorghum plants in salt affected soil as affected by organic

materials Composted with rock phosphate. *Pakistan Journal of Botany*, 46 (1):

173 - 180.

- Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. and Zhang, F. (2011).** Phosphorus Dynamics: from soil to plant. *Plant physiology* 156: 997–1005
- Singh, B. and Gilkes, R.J. (1991).** Phosphorus sorption in relation to soil properties for the major soil types of South- Western Australia. *Aust J Soil Res* 29 : 603 - 618.
- Sleutel, S., Moeskops, B., Huybrechts, W., Vandenbossche, A., Salomez, J., De Bolle, S., Buchan, D. and De Neve, S. (2008).** Modeling soil moisture effects on net nitrogen mineralization in loamy wetland soils. *Wetlands soils of West Africa. Soil Sci.* 124: 370 - 376.
- Smeck, N.E. (1985).** Phosphorus dynamics in soils and landscapes. *Geoderma.* 36: 185-199.
- Somado, E.A., Becker, M. and Kuehme, R.F. (2003).** Combined effect of legumes with rock phosphorus on rice in West Africa. *Agron. J* 95: 1172 – 1178
- Srinivasa, R., Anand, S., Subba, R. and Raja, G.V. (1999).** Kinetics of non-exchangeable potassium release from a tropaquet as influenced by long- term cropping, fertilization and manuring. *Australian Journal of Soil Research* 37: 317- 328
- Straaten, P.V. (2002).** Rocks for crops, agro minerals of sub-Sahara Africa. (CD), ICRAF, Nairobi, Kenya. ISBN: 0-88955-512-5,pp
- Stuanes, A.O. (1982).** Phosphorus sorption by soil: A review. In A.S. Eikum. and R.W. Seasloom, (eds,) *Alternative Wastewater Treatment*. Reidel Publ. Co., Hingham, MA. PP 145 - 152
- Sustrac, G. (1986).** BRGM phosphate prospecting methods and results in West Africa. *Trans. Instn. Min. Metall. (Sect. A: Min. Industry)* 95 : 134 - 143

- Szilas, C., Semoka, J.M.R. and Borgaard, O.K. (2007).** Establishment of an agronomic database for Minjingu phosphate rock and example its potential use. Nutrient Cycling in Agroecosystem 78: 225 - 237.
- Taalab, A.S. and Badr, M.A. (2007).** Phosphorous availability from compacted rock phosphate with nitrogen to sorghum inoculated with Phospho –bacterium. J. Appl. Sci. Res 3(3): 195 - 201.
- Tan, K. H. (1998).** Principles of soil chemistry. Third Edition. Marcel Dekker, Inc. Madison Avenue, New York.
- Tangyuan, N., Bin, H., Nianyuan, J., Shenzhong, T. and Zengjia, L. (2009).** Effects of conservation tillage on soil porosity in maize-wheat cropping system. Plant, Soil and Environment 55: 327 – 333.
- Teng, Y. and Timmer, V.R. (1994).** Nitrogen and phosphorus interaction in an intensively managed nursery soil plant system. Soil Sci Soc of America R. J 58 (1): 232-238.
- Thomas, G. W. (1982).** “Exchangeable cations,” .In: A. L. Page, R. H. Miller, and R. Keeney .(1982). Methods of soil analysis, Part 2, chemical and microbiological properties, agronomy monograph (9): 159 –165, American Society of Agronomy, Madison, Wis, USA, 2nd edition.
- Thuita, M.N., Okalebo, J.R., Othieno, C.O., Kipsat, M.J., Batiano, A., Sanginga, N. and Vanlauwe ,B.(2005).** An attempt to enhance solubility and availability of phosphorus from phosphate rocks through incorporation of organics in western Kenya. African Crop Science Conference Proceedings. (7): 1021 - 1027.
- Tiessen, H. and Moir, J.O. (1993).** Characterization of available P by sequential extraction. In M.R. Carter, (Ed.) Soil sampling and methods of analysis. Canadian Society of Soil Science Lewis Publ.,Boca Raton, FL.

- Traore, K.B., Gigou, J.S., Coulibaly, H. and Doumbia, M.D. (2004).** Contour ridgetillage increases cereal yields and carbon sequestration. ISCO -13th conference
Brisbane.
- Truong, B., Pichot, J. and Beunard, P. (1978).** Caractérisation et comparaison des phosphates naturels tricalciques d'Afrique de l'Ouest en vue de leur utilisation directe en agriculture. *Agron. Trop* 33: 136-145
- Uchida, R. (2000).** Essential nutrients for plant growth: Nutrient functions and deficiency symptoms. In: N. V. Hue., R. L. Fox. (2010). Predicting plant phosphorus requirements for Hawaii soils using a combination of phosphorus sorption isotherms and chemical extraction methods *Communications in soil Science and Plant Analysis*, 41: 133 –143.
- Uwumarongie-Ilori, .E.G., Oviasogie, P.O. and Aghimien, A.E.(2012).** Evaluation of rock phosphate-phosphorus sorption and release in basement complex soil cultivated to the Oil Palm. *Journal of Agricultural Research and Development* 2 (3): 070 - 076.
- Villarino, S. H., Stoddert, G. A., Laterra, P. and Cendoya, M. G. (2014).** Agricultural impact on soil organic carbon content: Testing the IPCC carbon accounting method for evaluations at county scale. *Agriculture, Ecosystems & Environment* 185: 118 – 132
- Wang, X., Yost, R.S. and Linquist, B.A. (2001).** Soil aggregate size affects phosphorus desorption from highly weathered soils and plant growth. *Soil. Sci. Am.J.* 65: 139 - 146.
- Warren, G. (1992).** Fertilizer phosphorus sorption and residual value in tropical African soils. NRI Bull. 37. Nat. Resour. Inst., Chatham, England.

- Wasonga, C.J., Sigunga, D.O., Musandu, A.O. (2008).** Phosphorus requirements by maize varieties in different soil type of western Kenya. African Crop Science Journal 2 (16): 161 - 173
- Weil, S., Gregg, P.E.H. and Bollan, N.S. (1994).** Influence of soil moisture on the dissolution of reactive phosphate rocks. In Zapata, F. and Roy, R. N. (2004). Use of phosphate rocks for sustainable agriculture. FAO. Fertilizer and Plant Nutrient Bulletin 13. Rome-Italy.
- Wicks, G.A., Smika, D.E. and Hergert, G.W. (1988).** Long-term effects of no-tillage in a winter wheat (*Triticum aestivum*)–sorghum (*Sorghum bicolor*)–fallow rotation. Weed Sci 36 : 384 – 393.
- Wortmann, C.S., Mamo, M. and Doberman, A. (2007):** Nitrogen response of grain sorghum in rotation with soybean. Agron. J. 99 : 808 - 813.
- Wright, R.J., Baligar, V.C., Belesky, D.P. and Snuffer, J.D. (1991).** The effect of phosphate rock dissolution on soil chemical properties and wheat seedling root elongation. Plant and soil 134: 21 - 30 Kluwer Academic Publishers.
- Yamoah, C.F., Bationo, A., Shapiro, B. and Koala, S. (2002).** Trend and stability analysis of millet yields treated with fertilizer and crop residues in the Sahel. Field Crops Res 75: 53 - 62.
- Yang, J.E. and Jacobsen, F. (1990).** Soil inorganic phosphorus fractions and their uptake relationship in calcareous soils. Soil Science Soc. Am 54: 1666 - 1669.
- Zaher, A. and Abouzeid, M. (2007).** Physical and thermal treatment of phosphates ores- An overview. Int. J. Miner. Process (85): 59 - 84.
- Zapata, F. and Roy, R. N. (2004).** Use of phosphate rocks for sustainable agriculture. FAO. Fertilizer and Plant Nutrient Bulletin 13. Rome-Italy.

Zin, Z.Z., Zulkifli, H., Tarmizi, A.M., Hama-dan, A.B., Khalid, H. and Raja,

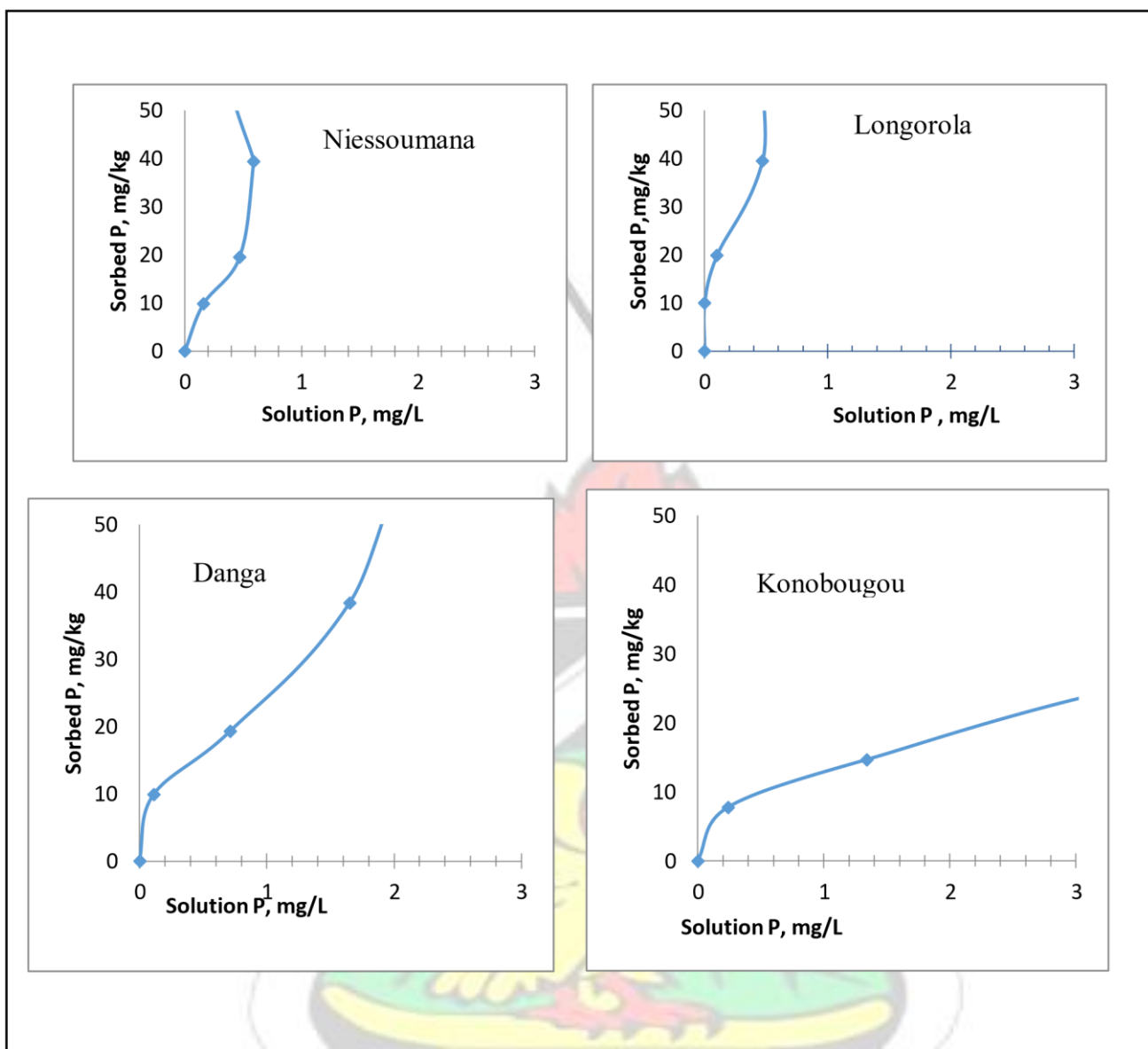
Z.R.O. (2005). Rock phosphate fertilizers recommended for young oil palm planted on inland soils. MPOB information series. ISSN 1511-7871. Journal of Science and Technology © KNUST

KNUST



APPENDICES

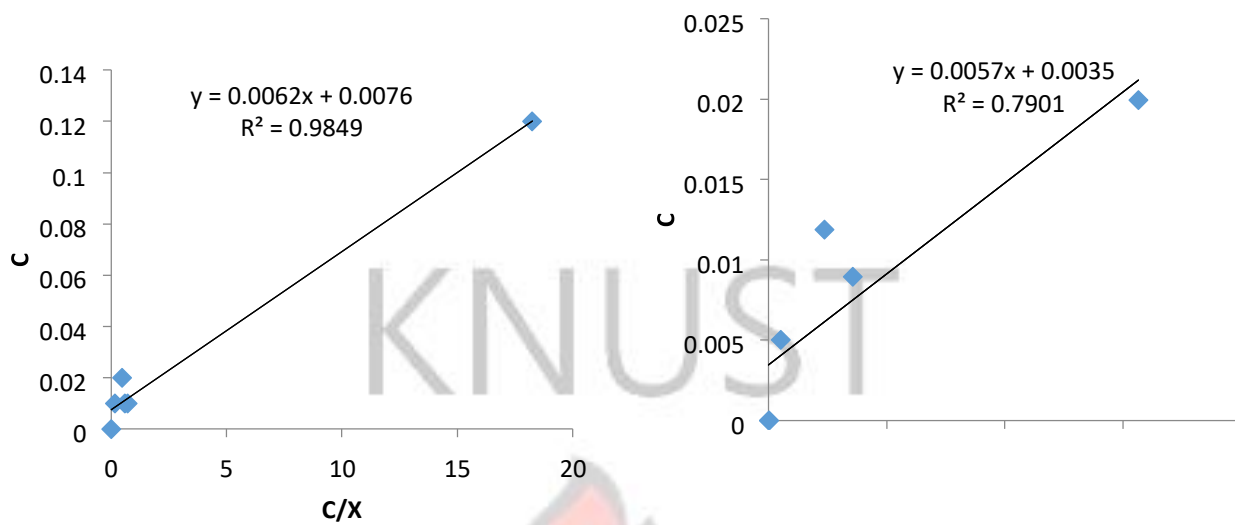
Appendix 1a: Phosphorus sorption isotherm curves for selected soils.



Appendix 1b: Langmuir model for the soils under study

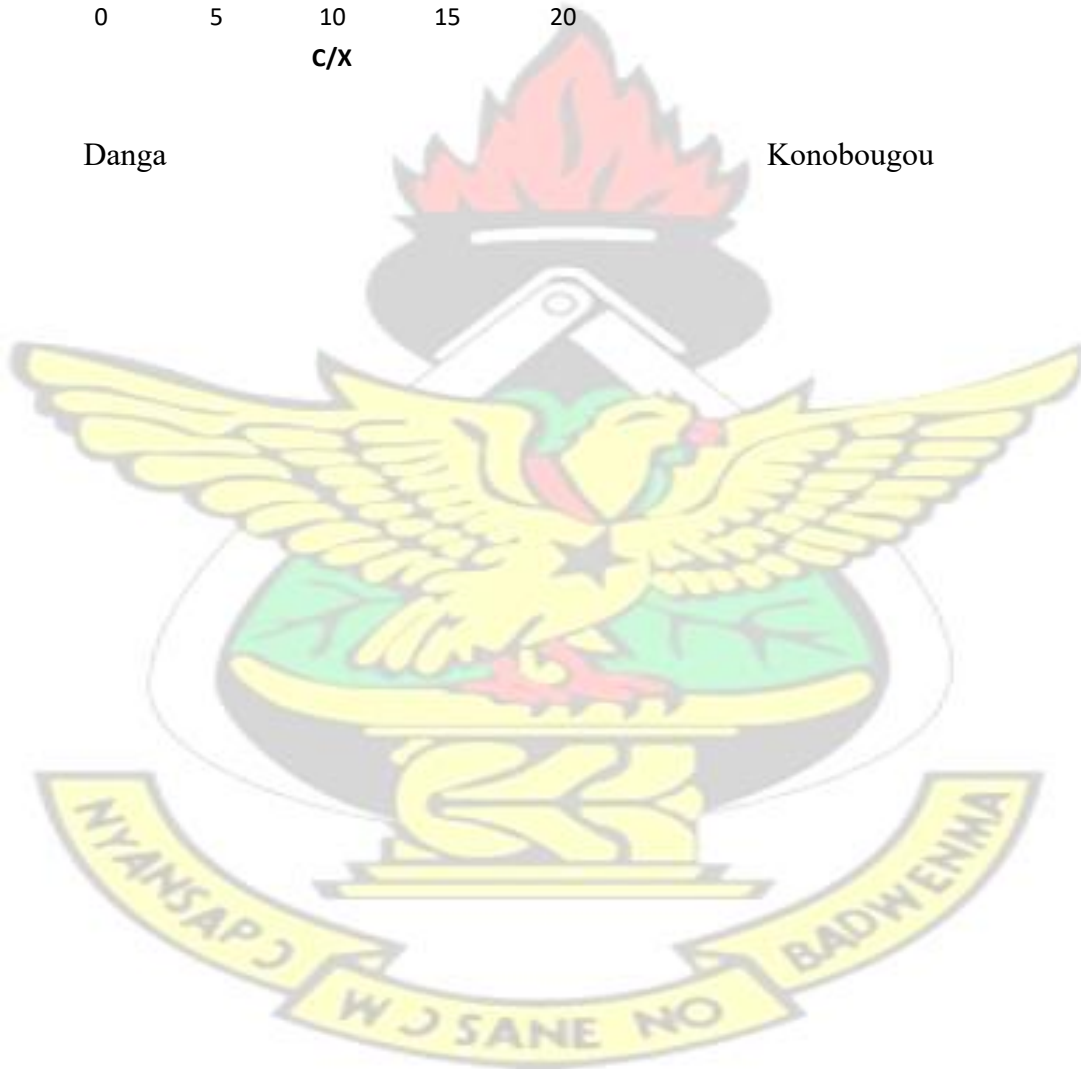
Niessoumana

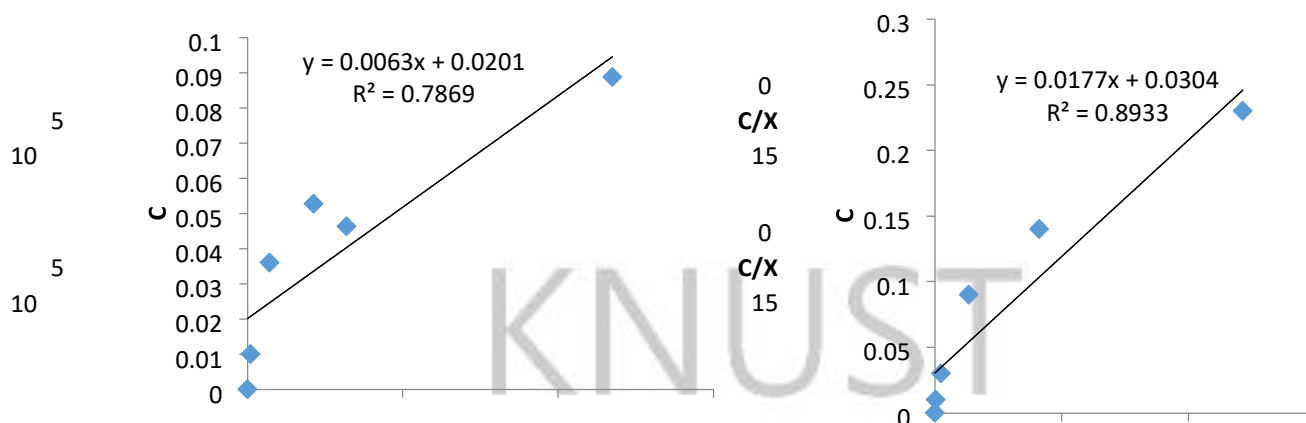
Longorola
LongLongorola



Danga

Konobougou





Appendix 2a: Year effect on soil chemical properties under maize cultivation

Sources of variation	P Values								
	pH	C	N	P	ExchCa	ExchK	ExchMg	Exch.ac	ECEC
		-----(%)-----		mg/kg	-----cmol.kg ⁻¹ -----				
Year	<.001	<.001	<.001	<.016	0.001	0.083	0.04	0.012	<.001
TPx Year	0.87	0.27	0.46	0.001	0.70	0.031	0.66	0.006	0.49
PS x Year	<.001	0.03	<.001	0.031	0.062	0.65	<.001	0.40	0.007
PR x Year	0.001	0.19	<.001	0.016	0.016	0.77	0.17	0.97	0.03

Appendix 2 b: Year effect on P and N uptake by maize

Sources of variation	P Values			
	Grains	Biomass	Grain P uptake	Biomass P uptake
	----- (kg ha ⁻¹) -----			
Year	0.94	0.46	<.001	<.001
TPx Year	0.51	0.15	<.001	0.28
PS x Year	0.79	0.54	<.001	0.002

PR x Year	0.68	0.99	<.001	<.001
-----------	------	------	-------	-------

KNUST

Appendix 3a Year effect on soil chemical properties under sorghum cultivation

Sources of variation	P Values								
	pH	C	N	P	Ca	K	Mg	Al+H	ECE C
	-----	(%)	---	mg/kg	-----	cmol _c kg ⁻¹	-----	---	---
PS	<.001	0.9-5	0.005	<.001	<.001	<.001	<.001	<.001	<.001
PR	<.001	0.26	0.13	<.001	<.001	<.001	<.001	<.001	<.001
Year	0.22	0.01	0.002	0.005	<.001	<.001	<.001	0.76	<0.04
PS x Year	<.001	0.97	0.51	0.09	0.03	<.001	0.01	0.92	0.31
PR x Year	<.001	0.28	0.28	0.901	0.33	0.24	0.20	0.09	0.8

Appendix 3b Year effect on sorghum yields P and N uptake

Sources of variation	P Values					
	Grains	Biomass	Grain P	Biomass P	Grain N	Biomass N
	-----	-----	-----	-----	-----	-----
PS	<.001	<.001	0.002	<.001	<.001	<.001
PR	<.001	<.001	<.001	<.001	<.001	<.001

Year	<.001	<.001	<.001	<.001	<.001	<.001
PS x Year	0.31	0.007	0.01	0.053	0.053	<.001
PR x Year	0.80	<.001	<.001	<.001	<.001	<.001

KNUST

Appendix 4: Effect of soil amendment on sorghum growth rate (CGR)

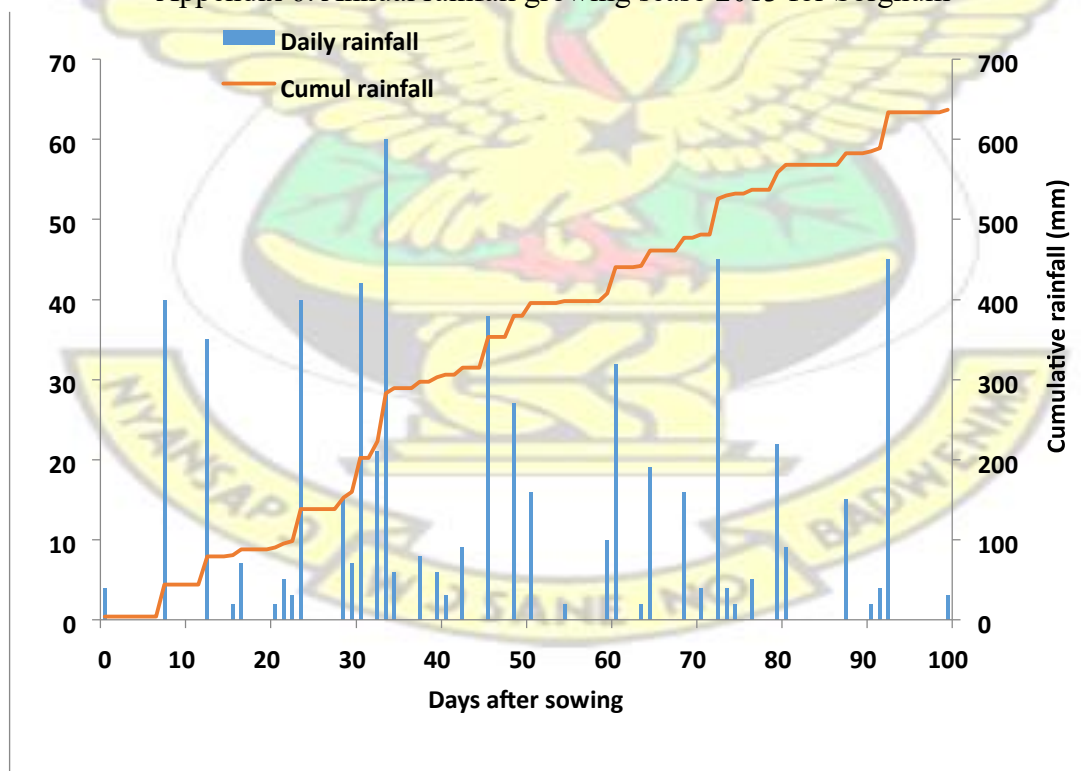
Years	2013		201	
	C1(g m ⁻² d ⁻¹)	C2(g m ⁻² d ⁻¹)	C1(g m ⁻² d ⁻¹)	C2(g m ⁻² d ⁻¹)
	21-42 DAS	43-64 DAS	21-42 DAS	43-64 DAS
Phosphorus source (PS)				
Ctrl	1.54	8.00	3.20	10.00
Pellet	1.98	15.80	5.24	18.10
P+K	2.98	20.60	3.63	20.60
P+SAM	4.61	29.40	11.48	31.70
P+K+SAM	3.15	27.00	7.30	29.10
Lsd	1.032	6.910	2.28	7.64
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Phosphorus rate (PR)				
0	1.70	10.20	3.19	12.50
11	3.27	19.30	7.51	22.40
16	3.59	31.00	7.80	30.90
Lsd	0.800	5.35	1.77	5.92
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Interaction PS x PR				
Fpr	0.015	0.003	< 0.001	0.004
CV (%)	37.50	35.40	38.30	36.10

Appendix 5: Sorghum height

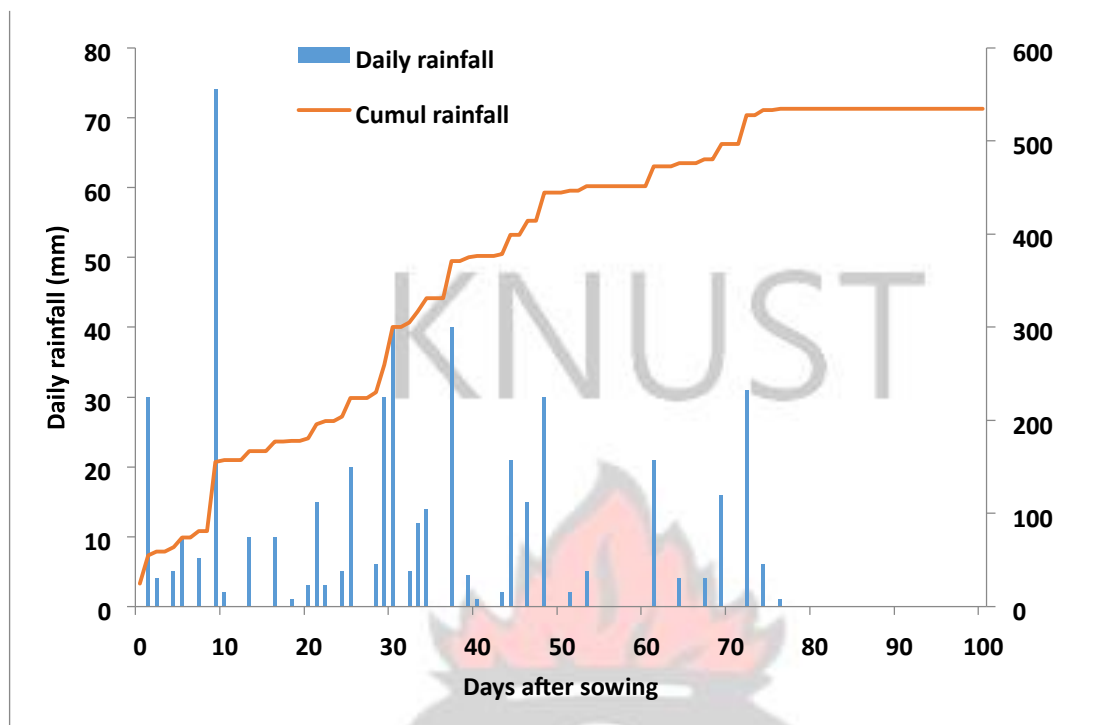
Sorghum Height (m)

Years	2013	2014
Phosphorus Source (PS)		
Ctrl	1.41	1.47
Pellet	1.15	1.29
P+K	1.50	1.51
P+SAM	1.40	1.69
P+K+SAM	1.54	1.62
Lsd	0.28	0.172
Fpr	0.075	<.001
Phosphorus Rate (PR)		
0	1.22	1.40
11	1.49	1.55
16	1.49	1.59
Lsd	0.22	0.13
Fpr (0.05)	0.02	0.01
Interaction PS x PR		
Fpr (0.05)	0.331	< 0.001
CV (%)	21.20	11.80

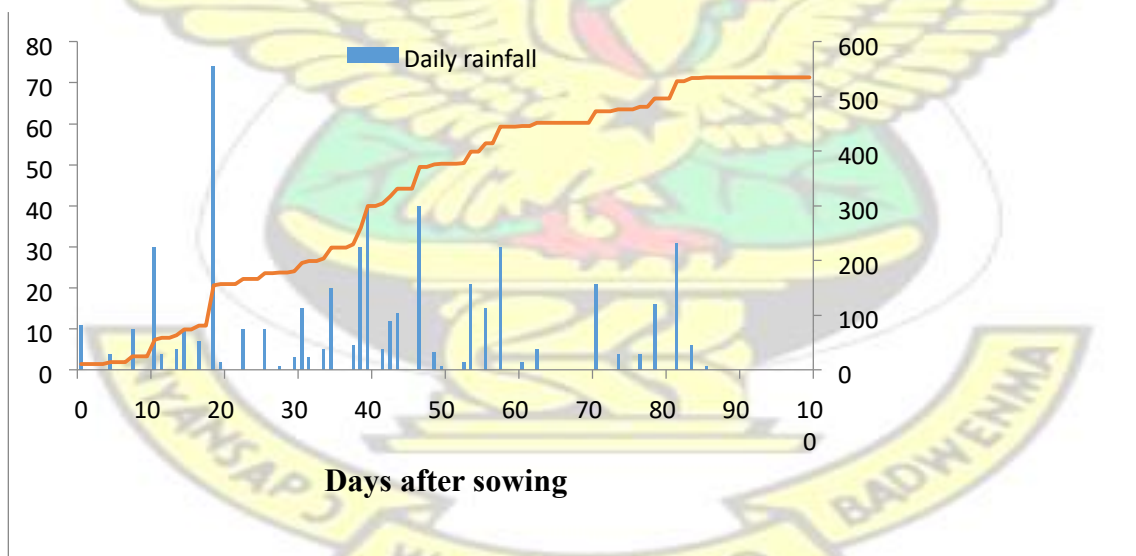
Appendix 6: Annual rainfall growing seaso 2013 for Sorghum



Appendix 7: Annual rainfall growing season 2014 for Sorghum



Appendix 8: Annual rainfall growing season 2013 for Maize



Appendix 9: Annual rainfall growing season 2014 for Maize

