University of Ghana http://ugspace.ug.edu.gh

ENHANCING GENETIC VARIABILITY FOR PHOSPHORUS-USE EFFICIENCY IN SORGHUM (*Sorghum bicolor* L. Moench) USING CHEMICAL MUTAGENESIS

BY

AZU, ELAINE

(10235622)

THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY DEGREE IN PLANT BREEDING

WEST AFRICA CENTRE FOR CROP IMPROVEMENT

COLLEGE OF BASIC AND APPLIED SCIENCES

UNIVERSITY OF GHANA

LEGON

December, 2017

University of Ghana http://ugspace.ug.edu.gh

DECLARATION

I hereby declare that except for references to works of other researchers, which have been duly cited, this work is my original research and that neither part nor whole has been presented elsewhere for the award of a degree.

……..

AZU, ELAINE
(Student)

……
PROF HARRY M. AMOATEY
(Supervisor)

……
PROF ERIC Y. DANQUAH
(Supervisor)

……
DR. ERIC NARTEY
(Supervisor)

University of Ghana http://ugspace.ug.edu.gh

ABSTRACT

In Ghana, sorghum (*Sorghum bicolor* L. Moench) ranks third after maize and rice, mainly as a dietary staple and is crucial for ensuring food security in the three northern regions. However, yields in farmers' fields are extremely low (less than 2.0 tonnes ha^{-1}) compared to the 4.5 to 5.0 tonnes ha^{-1} achievable in developed countries. A series of investigations were therefore carried out to identify farmers' production constraints to facilitate development of strategies towards finding sustainable, long-term solutions within the context of plant breeding. A participatory rural appraisal was therefore conducted among smallholder sorghum farmers in four communities in the Talensi-Nabdam and Binduri districts of the Upper East Region of Ghana. The survey also sought to determine farmers' perceptions of soil fertility as well as their current soil management strategies. Data were collected through focus group discussions, questionnaires and direct field observations. Within the communities, drought, high cost of farm input (labour and ploughing services) and declining soil fertility were the most important constraints to sorghum production. In spite of widespread low soil fertility, soil management methods such as fertiliser application, cover cropping and retention of crop residues were seldom practiced within the communities. Drought tolerance, high grain yield, earliness, grain quality (suitability for local foods and beverages) as well as low fertiliser requirement were the most preferred sorghum traits. Considering resources available to farmers and researchers in Ghana, mutation induction was considered a workable strategy in a breeding programme to expand the genetic diversity in the crop towards selection of phosphorus (P) use efficient genotypes. Mutation induction was achieved through chemical treatment of an inbred sorghum line BTx623 using ethyl methanesulphonate. A subset of 547 mutagenised lines at M_3 generation were subjected to phenotypic assessment for expression of key morpho-agronomic traits of sorghum, both quantitative and qualitative.

University of Ghana http://ugspace.ug.edu.gh

Significant differences ($p < 0.05$) were observed among the M_3 families for all the traits studied as well as between the families and BTx623. High genotypic coefficients of variation (GCV) established the existence of considerable variability. Broad sense heritability was also high ranging from 0.68 for stem girth to 0.99 for number of leaves. Positive and significant ($p < 0.05$) correlations were detected between grain yield and number of leaves, panicle width and stem girth. Principal component analysis revealed three principal components that accounted for 64% of the total variability. Grain yield (0.364), panicle width (0.436) and panicle length (0.411) were the most contributing traits. Hierarchical agglomerative clustering based on Unweighted Pair Group Method with Arithmetic mean (UPGMA), resolved the population into three divergent clusters at 52% level of dissimilarity. Two hundred and fifty three M_3 lines were grouped into clusters separate from the wildtype BTx623, which indicates considerable variability between the mutagenised lines and the control. Close inspection for novel or distinct phenotypes revealed putative mutants for brown midrib, erect leaf and bloomless traits. Considerable genetic variability exists within the population which can be exploited for further breeding work. Further, genetic variation for P-use efficiency among the mutagenised lines was evaluated alongside selected cultivated varieties. Two hundred lines, comprising 170 mutagenised lines (agronomically-superior) and 30 cultivated varieties were evaluated under screen-house and field conditions and in two contrasting soil-P environments using a randomized complete block design and an augmented (incomplete block) design respectively. Measured traits included seedling vigour, days to anthesis, yield (grain and stover) as well as P concentration in the grain and stover. Analysis of variance for each P environment revealed significant ($p <0.01$) differences among the genotypes for all measured traits. Combined analysis of variance also showed significant ($p <0.01$) effects between genotype and P environment for all traits except plant height and stem girth, indicating

University of Ghana http://ugspace.ug.edu.gh

differences in genotypic response under contrasting P environments. Overall, grain and stover yield decreased by 49 and 27% respectively with the omission of P. Based on Pearson's correlation analysis, grain yield was positively ($p < 0.05$) correlated with stover yield and P utilisation for grain production, but negatively correlated with P utilisation for stover production in both P environments, respectively. On the other hand, the relationship between stover yield and harvest index was significant ($p < 0.05$) in low-P soils but not significant in optimum-P soils. The contribution of each trait to observed genetic variation was determined by principal component analysis. The first three principal components (PC1, PC2 and PC3) explained 77% and 79% of the total variation in the low-P and optimum-P environments respectively. Traits that contributed the most variability in both P-environments were grain and stover yield. Subsequently, cluster analysis using UPGMA categorised the 200 genotypes into three divergent clusters at 49% dissimilarity. Cluster I, II and III contained 65, 106 and 29 genotypes respectively. Cluster I was characterised by reduced height and relatively late anthesis, Cluster II comprised the genotypes such as Grinkan, MR732, KuyumaWSV387 and CE151262A1 which produced the highest grain (mean = 56 g/plant) and stover yield (mean = 164 g/plant) whereas the genotypes in Cluster III were the tallest (mean height = 106 cm) in the population. The lines were then classified into four categories as P-uptake efficient, P-utilisation efficient, low-P stress tolerant or low-P stress sensitive, based on relative performance of the genotypes in both P environments. Kadaga West and Mut3412 were the most tolerant to low-P stress. Grinkan and ICSV1049 were the most P-uptake efficient whereas TxARG1 and Mut3708 were the most P-utilisation efficient. A comparison between the top-ranked mutant lines and cultivated genotypes indicated that the cultivated genotypes were more efficient at P-uptake whereas the putative mutants were more efficient at P-utilisation. There is potential to exploit the genotypic variability observed within the population for further breeding work. The

University of Ghana http://ugspace.ug.edu.gh

identified P-use efficient mutagenised lines may either be released directly as mutant varieties following multi-locational trials or used as parents in future recombinant breeding programmes.

University of Ghana http://ugspace.ug.edu.gh

DEDICATION

This thesis is dedicated to Adwoa, Ama and Aseda Elegba. Be encouraged.

University of Ghana http://ugspace.ug.edu.gh

ACKNOWLEDGMENTS

I am grateful to the West African Centre for Crop Improvement (WACCI) and the Alliance for a Green Revolution in Africa (AGRA) for providing the scholarship and logistics that were necessary to undertake my studies.

I thank the Bill and Melinda Gates Foundation, which through Purdue University, USA provided funds for aspects of my work and gave me the opportunity to visit the Department of Agronomy, Whistler Centre for Carbohydrate Research, West Lafayette. I am particularly grateful to Dr. Mitch Tuinstra and Dr. Cliff Weil for the wealth of knowledge and experience I gained during my time at Purdue University. Thank you for sharing your germplasm with me. I am exceeding grateful to Prof. Eric Yirenkyi Danquah for the opportunity to work with the team at Purdue University.

I am deeply grateful to my supervisors, Prof. Harry M. Amoatey, Prof. Eric Yirenkyi Danquah and Dr. Eric Nartey for their support and guidance throughout the entire study and to Prof. Kwadwo Ofori for his guidance and encouragement. My sincerest thanks also goes to all staff of WACCI and my colleagues, both past and present. You all made my time at WACCI memorable.

I am grateful to Ghana Atomic Energy Commission for granting me the study leave required to complete this degree. I thank the Director of BNARI, Prof Kenneth Ellis Danso for the support of the institute, both infrastructural and technical. To all staff at the Biotechnology Centre of BNARI, particularly Mrs. Abigail Asare, Ms. Vida Adu Afrakoma, Ms. Patience Asare, Mr. Clement Annor, and Mr. Samuel Azure who in diverse ways helped to make this work successful, I am grateful.

Special thanks go to staff of University of Ghana research farm particularly Mr. Agyekum and Mr. Stephen Atsu. Your unwavering support is fully-recognised and deeply-appreciated. To Mr.

University of Ghana http://ugspace.ug.edu.gh

Precious Blege of the University of Development Studies and the late Mr. Mohammed of the MoFA office, Talensi-Nabdam, I am grateful for the insight and guidance during the participatory rural appraisal in the Upper East Region of Ghana.

Mr. James Azu and Ms. Irene Garbrah, my parents as well as Samuel Azu, my brother, I deeply appreciate your sacrifice and encouragement. Wilfred, you encouraged me like no other. I am eternally grateful. Adwoa, Ama and Aseda, you bore the brunt of this challenging period. Thank you for bearing with me.

Finally, to you heavenly Father, only You are worthy. Thank you for grace. Indeed, you are the lifter up of my head.

University of Ghana http://ugspace.ug.edu.gh

TABLE OF CONTENTS

DECLARATION..... ii

ABSTRACT..... iii

DEDICATION..... vii

ACKNOWLEDGMENTS..... viii

LIST OF ABBREVIATIONS..... xxi

CHAPTER ONE..... 1

1.0 GENERAL INTRODUCTION..... 1

CHAPTER TWO..... 7

2.0 LITERATURE REVIEW..... 7

2.1 Origin domestication and distribution of sorghum..... 7

2.2 Classification of sorghum..... 8

2.3 Sorghum production..... 10

2.4 Uses of sorghum..... 11

2.5 Edaphic and nutrient requirements of sorghum..... 12

2.6. Phosphorus in soils..... 15

2.6.1 Forms of phosphorus in soils..... 15

2.6.2 Phosphorus availability and its acquisition by plants..... 16

2.6.3 Phosphorus status of West African soils..... 18

2. 7 Effect of phosphorus deficiency on sorghum productivity in West Africa..... 19

University of Ghana http://ugspace.ug.edu.gh

2.8 Crop adaptation to soil P deficiency 20

2.8 Strategies for improving sorghum productivity in low P soils 22

2.8.1 Traditional management strategies 22

2.8.2 Breeding strategies 24

2.8.2.1 Conventional approaches to breeding for phosphorus-use efficiency 24

2.8.2.2 Molecular approaches to breeding for phosphorus-use efficiency 27

2.8.2.3 Induced mutagenesis as an alternative breeding approach 28

CHAPTER THREE..... 31

3.0 FARMERS' PRODUCTION CONSTRAINTS, PERCEPTIONS OF SOIL FERTILITY AND PREFERENCE FOR SORGHUM TRAITS 31

3.1 Introduction 31

3.2 Materials and methods 34

3.2.1 Description of study sites 34

3.2.2 Sampling procedure and data collection techniques 36

3.2.3 Data analysis 37

3.3 Results 37

3.3.1 Demographic characteristics of households 37

3.3.2 Socio-economic characteristics of households 39

3.3.3. Farm size, area allocated to sorghum and estimated grain yield 41

3.3.4 Sources of seed and information 43

University of Ghana http://ugspace.ug.edu.gh

3.3.5 General constraints to sorghum production 44

3.3.6 Farmers' description and perception of soil fertility 46

3.3.7 Farmers' cropping systems and soil management practices 49

3.3.8 Cultivated sorghum varieties and farmers' preference for traits 51

3.4 Discussion 54

3.5 Conclusions 60

CHAPTER FOUR 61

4.0 PHENOTYPIC ANALYSES FOR IDENTIFICATION OF ARTIFICIALLY-INDUCED VARIABILITY IN SORGHUM 61

4.1 Introduction 61

4.2 Materials and methods 63

4.2.1 Description of study site 63

4.2.2 Generation of mutagenised population 64

4.2.4 Experimental design and layout 65

4.2.5 Data collection 66

4.2.6 Data analysis 67

4.3. Results 68

4.3.1 Variation within the mutagenised population for quantitative traits 68

4.3.2. Genetic and phenotypic variances and heritability within the mutagenised population 73

University of Ghana http://ugspace.ug.edu.gh

4.3.3 Correlation between the studied traits 74

4.3.5 Divergence between the genotypes based on cluster analysis 79

4.3.6 Variation within the mutagenised population for qualitative traits 83

4.5 Discussion 94

4.6 Conclusion 98

CHAPTER FIVE 99

5.0 GENETIC VARIATION FOR PHOSPHORUS-USE EFFICIENCY AMONG MUTAGENISED SORGHUM LINES 99

5.1 Introduction 99

5.2 Materials and methods 101

5.2.1 Evaluated genotypes 101

5.2.2 Description of study sites 103

5.2.3 Soil sampling and analyses 103

5.2.4 Experimental design and layout 104

5.2.5 Data collection 105

5.2.6 Data analysis 107

5.2.6.1 Data analysis for pot experiments 107

5.2.6.2 Data analysis for field experiment 109

5.3 Results 112

5.3.1. Pot experiment 112

University of Ghana http://ugspace.ug.edu.gh

5.3.1.1. Characteristics of soils in pot experiment..... 112

5.3.1.2. Genetic variation among the genotypes under contrasting P environments..... 112

5.3.1.3. Correlation between morpho-agronomic traits and P-tolerance ratios..... 117

5.3.1.4. Principal component analyses under contrasting P environments 119

5.3.1.5. Variation within the population based on cluster analysis. 123

5.3.1.6. Relative performance of the genotypes in contrasting P environments...... 126

5.3.1.7. Selection of P-use efficient genotypes..... 126

5.3.2. Field experiment..... 128

5.3.2.1. Characteristics of soils in field experiments 128

5.3.2.2. Genotypic variation for morpho-agronomic traits in contrasting P environments128

5.3.2.3. Genotypic variation for P-use efficiency indicators in contrasting P environments

..... 133

5.3.2.4. Heritability and genotypic coefficient of variation within the population..... 138

5.3.2.5. Correlation between morpho-agronomic traits and P-use efficiency indicators in contrasting soil-P environments 139

5.3.2.6. Differences between mutants and cultivated varieties for morpho-agronomic traits

..... 142

5.3.2.7. Selection of low soil P-stress tolerant and sensitive genotypes 145

5.4 Discussion..... 148

5.6 Conclusions..... 151

University of Ghana http://ugspace.ug.edu.gh

CHAPTER SIX 153

6.0 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS 153

REFERENCES 156

APPENDIX 187

Appendix 1: PRA questionnaire 187

Appendix 2: p- values for Pearson's correlation coefficient of quantitative traits among 550 genotypes 193

Appendix 3: Members of individual clusters in Figure 4.5 194

Appendix 4: Procedures for soil characterization and analysis 197

Appendix 5: Determination of phosphorus in leaf and grain samples 200

Appendix 6: Names of putative mutants (codes) used in PCA biplot of 200 genotypes as shown in Figure 5.3 201

Appendix 7: Distribution of 200 genotypes in three clusters – Figure 5.4 203

University of Ghana http://ugspace.ug.edu.gh

LIST OF FIGURES

Figure 3.1. Geographical representation of Talensi-Nabdam and Binduri districts. 35

Figure 3.2. Sources of seed and (A) and information (B) across the communities 51

Figure 3.3. Diversity of sorghum varieties cultivated in the communities 51

Figure 4.1. Box plots showing the distribution of studied traits in the mutagenised population.. 71

Figure 4.2. Loading plot of PC1 and PC2 showing contribution of quantitative traits to variability 78

Figure 4.3. Distribution of sorghum genotypes for first two principal components..... 79

Figure 4.4. Dendrogram of 550 sorghum genotypes derived by UPGMA method (Pearson's dissimilarity matrix)..... 81

Figure 4.5. Boxplots showing the distribution of traits in each cluster. 82

Figure 4.6a: Variations in leaf midrib and blade colour 88

Figure 4.6b: Variations in leaf colour 89

Figure 4.6c: Variations in leaf size 90

Figure 4.7d: Variations in plant architecture 91

Figure 4.6e: Variations in tillering and panicles 92

Figure 4.6f: Variations in bloom: Senescence and wilting 93

Figure 5.1. Distribution of traits in low and optimum P-environments. 114

Figure 5.2. Loading plot of PC1 and PC2 showing contribution of morpho-agronomic traits to variability 121

Figure 5.3. Distribution of the 200 genotypes for PC1 and PC2 122

Figure 5.4. Dendrogram of 200 sorghum genotypes derived by UPGMA method (Pearson's dissimilarity matrix)..... 124

University of Ghana http://ugspace.ug.edu.gh

Figure 5.5. Boxplots showing the distribution of traits in each cluster 125

University of Ghana http://ugspace.ug.edu.gh

LIST OF TABLES

Table 3.1. Number of respondents across the study sites 36

Table 3.2. Demographic characteristics of households 38

Table 3.3. Socio-economic and farm characteristics of households 40

Table 3.4. Farm size and area allocated to sorghum within the communities 42

Table 3.5. Ranking of sorghum production constraints across the four communities 45

Table 3.6. Farmers' description of soils 47

Table 3.7. Farmers' perceptions of soil fertility and its effect on sorghum 48

Table 3.8 Farmers' cropping systems and soil management practices 50

Table 3.9. Ranking of farmers' preference for sorghum traits 53

Table 4.1. Meteorological data for the sites during the study period 64

Table 4.2. Descriptive statistics of nine evaluated traits 70

Table 4.3. Analysis of variance within the mutagenised population for quantitative traits 72

Table 4.4 Summary of estimated variances and heritability for quantitative traits 73

Table 4.5. Pearson's correlation coefficients of quantitative traits among 550 genotypes 75

Table 4.6. Eigenvalues of first three principal components 77

Table 4.7. Percentage contribution (%) of the traits PC1, PC2 and PC3 77

Table 4.8. Mutant phenotypes segregating in M_3 families 86

Table 5.1. Summary of the cultivated genotypes and their important features 102

Table 5.2. Meteorological data for the experimental areas during the study period 103

Table 5.3 Descriptions of evaluated traits 106

Table 5.4. Format of ANOVA for two-way factorial experiment (RCBD) 107

Table 5.5. Estimations of P-uptake and utilisation parameters 111

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.1. Analysis of variance under contrasting P environments..... 115

Table 5.6.2. Comparison between means of traits in contrasting P environments 115

Table 5.6.3. Heritability, genetic and phenotypic variability of the traits under low-P stress.... 116

Table 5.6.4. Correlation coefficients between morpho-agronomic traits (under low P stress) .. 118

Table 5.6.5. Principal components of morpho-agronomic traits in the contrasting P environments 120

Table 5.6.6. Top-ranked (10%) genotypes for grain yield ratio, P-uptake and P-utilisation efficiencies 127

Table 5.6.7. Analysis of variance for morpho-agronomic traits in low-P stress 130

Table 5.6.8. Analysis of variance for morpho-agronomic traits under optimum soil P 131

Table 5.6.9. Comparison between means of traits in low P and optimum P environments 132

Table 5.7.1. Analysis of variance for P-uptake and use efficiency indicators in low P stress... 134

Table 5.7.2. Analysis of variance for P- uptake and use efficiency indicators under optimum soil P conditions..... 135

Table 5.7.3. Comparison between means of traits in low P and optimum P environments 136

Table 5.7.4. Combined analysis of variance for morpho-agronomic traits 137

Table 5.7.5. Combined analysis of variance for P- uptake and use efficiency traits 137

Table 5.7.6. Estimates of genetic variance, heritability and genotypic coefficient of variation in low and optimum P trials 138

Table 5.7.7. Correlation between morpho-agronomic traits and P-use efficiency indicators under low soil P conditions..... 140

Table 5.7.8. Relationship between yield components and P-use efficiency indicators under optimum soil P conditions 141

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.9. Highest-ranking mutants and cultivated genotypes for yield and PUE indicators . 144

Table 5.8.1. Top-ranked genotypes (grain yield) in low-P soil and their performance in optimum-P soil …….. 146
Table 5.8.2. Low-P stress tolerant and sensitive genotypes within the population 147

University of Ghana http://ugspace.ug.edu.gh

LIST OF ABBREVIATIONS

AGRA	Alliance for Green Revolution in Africa
ANOVA	Analysis of variance
ATP	Adenosine Triphosphate
BM	Biomass
BNARI	Biotechnology and Nuclear Agriculture Research Institute
CEC	Cation exchange capacity
CV	Coefficient of variation
DAP	Di-ammonium phosphate
DFR	Days to flowering ratio
DNA	Deoxyribonucleic Acid
DTF	Days to flowering
ECV	Environment coefficient of variation
EMS	Ethyl methanesulphonate
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistical Databases
GCV	Genotypic coefficient of variation
GSS	Ghana Statistical Service
GY	Grain yield
GYP	Grain yield per plant
GYR	Grain yield ratio
H^2	Broad sense heritability

University of Ghana http://ugspace.ug.edu.gh

HSW	Hundred seed weight
IAEA	International Atomic Energy Agency
IBM	International Business Machines
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
IFAD	International fund for agricultural development
IFDC	International Fertiliser Development Centre
K	Potassium
LMWOA	Low Molecular Weight Organic Acids
MAS	Marker Assisted Selection
MoFA	Ministry of Agriculture, Ghana
Mut	Mutant
N	Nitrogen
NL	Number of leaves
MNU	Methyl nitrosourea
NGOs	Non-Governmental Organisations
P	Phosphorus
PAE	Phosphorus Acquisition efficiency
PBM	Phosphorus content in biomass
PC	Principal Component
PCA	Principal Component analysis
PCG	Phosphorus concentration in grain
PCS	Phosphorus concentration in stover
PCV	Phenotypic coefficient of variation

University of Ghana http://ugspace.ug.edu.gh

PE	Peduncle exsertion
PG	Phosphorus content in grain
PH	Plant height
PHI	Phosphorus harvest index
PHR	Plant height ratio
PL	Panicle length
PRA	Participatory Rural Appraisal
PS	Phosphorus content in stover
PSTOL-1	Phosphorus Starvation Tolerance 1
PUE	Phosphorus Use Efficiency
Pup	Phosphorus Uptake Efficiency
PUP-1	Phosphorus Uptake 1
PUtE	Phosphorus Utilisation Efficiency
PUTIL-BM	Phosphorus utilisation for biomass production
PUTIL-G	Phosphorus utilisation for grain production
PUTIL-S	Phosphorus utilisation for stover production
PW	Panicle width
QTL	Quantitative Trait Loci
RILs	Recombinant inbred lines
REML	Restriction maximum likelihood
RNA	Ribonucleic acid
RUDEMA	Rural Development Management
SARI	Savannah Agriculture Research Institute

University of Ghana http://ugspace.ug.edu.gh

SG	Stem girth
SNP	Single-Nucleotide Polymorphisms
SPSS	Statistical Package for the Social Sciences
SSP	Single super phosphate
SVR	Seedling vigour ratio
TSBF	Tropical soil biology and fertility.
TSP	Triple super phosphate
UPGMA	Unweighted pair group method with arithmetic mean
USA	United State of America
USDA	United State Department Agency
VAM	Vesicular-Arbuscular Mycorrhiza

University of Ghana http://ugspace.ug.edu.gh

CHAPTER ONE

1.0 GENERAL INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is the fifth most important cereal in the world after wheat, maize, rice and barley (Dahlberg *et al*., 2011). In Africa, it is the second major cereal after maize and ranks third in Ghana after maize and rice (FAOSTAT, 2012). It is a highly versatile crop and is valued for both its grain and stover. In developed countries, its primary use is as feed for livestock and poultry as well as the production of ethanol (Rajasekher *et al*., 2005). On the other hand, in Africa, sorghum is a dietary staple and is crucial to the food security of over 500 million people (Dahlberg *et al*., 2011). Due to its ability to perform favourably under harsh and unpredictable climatic conditions, the crop provides a less risky alternative to sole maize cropping and is a reliable source of income for many smallholder farmers in the Sahelian and Savannah zones (Buerkert *et al*., 2001; Sultan *et al*., 2013).

Although sorghum is adapted to the harsh climatic and edaphic conditions of West Africa, yield in this region is low (Wang *et al*., 2010). Yield potential in West Africa is estimated at 2.0 to 3.0 tonnes/ha. However, in several countries, sorghum productivity is approximately 1.8 tonnes ha^{-1} (Wang *et al*., 2010). This is woeful compared to the 4.5 to 5.0 tonnes ha^{-1} produced by the USA and Europe (FAO, 2012). While sorghum cultivation in developed regions is commercial, high-input and highly productive, its production in West Africa is subsistent, low-input and characterised by the cultivation of inherently low-yielding varieties (FAO, 2010; Vom Brocke *et al*., 2010). Additionally, sorghum production in West Africa is constrained by drought, diseases such as downy mildew (*Peronosclerospora sorghi* [Weston and Uppal; (Shaw)]) and anthracnose (*Colletotrichum graminicola*) and pests such as midge (*Stenodiplosis sorghicola* Coquillett) and

University of Ghana http://ugspace.ug.edu.gh

shoot fly [*Atherigona soccata* (Rondani)] (Dhillon *et al*., 2005; Riyazaddin *et al*., 2016). Another key contributor to low sorghum yields in Africa is soil infertility (Leiser *et al*., 2014).

Soil infertility is a widespread problem in Africa; over 121 million hectares of the continent's total land is deficient in essential plant nutrients (Bationo *et al*., 2006). This is as a result of decades of unsustainable cropping systems leading to nutrient mining and erosion (Bationo *et al*., 2012). In northern Ghana for instance, major causes of soil infertility include nutrient mining and erosion worsened by seasonal bush fires, deforestation and overgrazing (Yahaya and Amoah, 2013). In general, the main soil nutritional constraint in small-scale farming systems in Africa is nitrogen (N) deficiency (Nziguheba, 2007). However, African soils are not only deficient in N but are extensively deficient in phosphorus (P) (Sweeney *et al*., 2011). In West African soils, P is one of the main limiting macronutrients with over 50% of arable land lacking sufficient quantities for maximum crop yield (Nandwa *et al*., 2011; Leiser *et al*., 2014). Smallholder fields rarely exceed the critical level of 15 mg P kg^{-1} and are often characterised by available P content of 7 to 10 mg P kg^{-1} (Doumbia *et al*., 1993; Buerkert et *al*., 2001). P levels as low as 2 to 5 mg P kg^{-1} have been reported in Mali and eastern Kenya (Obura, 2008; Leiser *et al*., 2012). According to Owusu-Bennoah and Acquaye (1996), available P in soils in northern Ghana varied from 1.7 to 8.7 mg P kg^{-1}. However, Nyanteng and Asuming-Brempong (2003) reported slightly higher values of between 4.38 and 9.43 mg P kg^{-1}.

The low P status of West African soils is a major constraint to sorghum production (Verde and Matusso, 2014). P deficiency results in poor seedling emergence and establishment and an overall reduction in crop growth leading to low yields (Buerkert *et al*., 2001). Poor sorghum yields coupled with increasing food demand as a result of rapid growth in human population threatens the food

University of Ghana http://ugspace.ug.edu.gh

security and livelihood of millions of people in West Africa. It has therefore become increasingly important to improve sorghum productivity in P-stressed soils.

Several strategies have been proposed to increase sorghum productivity on marginal soils in general. These include traditional practices such as shifting cultivation or land fallowing, crop rotation, cover cropping and intercropping (Samake *et al*., 2005). Unfortunately, in recent times, the use of these methods is limited by dwindling land availability, increasing population densities and other socio-economic pressures (Gregory and Bumb, 2006).

The key strategy for maintaining crop productivity on poor soils has been fertiliser application (AGRA, 2012). As with other crops, the application of fertilisers to sorghum fields has been shown to result in significant increases in grain yield (Kaizzi *et al*., 2012). However, in spite of demonstrated gains, sorghum cultivation in West Africa is characterised by little or no added nutrient input (Buah *et al*, 2012). Average fertiliser use in sub-Saharan Africa is estimated as 16.25 kg/ha, a sixth of the world's consumption of 98.20 kg/ha (Hernandez and Torero, 2011; Sommer *et al*., 2013). For instance fertiliser application rates in Ethiopia, Burkina Faso and Cameroon are estimated at approximately 18, 9 and 7 kg/ha compared to 125, 167 and 238 kg/ha in Brazil, India and the Netherlands respectively (FAO, 2009). Although recent reports indicate an increase in the application of N-based fertiliser, the use of P-based fertilisers has remained minimal at 2.2 kg/ha compared to 7.9 kg/ha in Latin America (Kelly, 2006; MacDonald *et al*., 2011). This imbalance in N and P levels has been reported as a major contributor to yield reductions (van der Velde *et al*., 2014). The main constraints to fertiliser-use in West Africa are cost of the commodity and its unavailability (van der Velde *et al*., 2014). Unfortunately, the impact fertiliser subsidy policies is diminished by huge fiscal and administrative costs, late delivery of subsidised fertilisers as well as smuggling (Druilhe and Barreiro-Hurle, 2012).

University of Ghana http://ugspace.ug.edu.gh

While increasing fertiliser use on smallholder sorghum fields in West Africa will undoubtedly improve yields, for mineral P fertilisers, this strategy is unsustainable. Mineral P is a finite resource. Rock phosphate reserves which account for 90% of inorganic P fertilisers are expected to be exhausted in 50 to 100 years (Cordell *et al*., 2009; Sattari *et al*., 2012). Thus, availability of inorganic P fertilisers is likely to be a major challenge in a few decades (Van Vuuren *et al*., 2010). Its unavailability is also likely to increase cost of the commodity, making it even more inaccessible to smallholder farmers in West Africa. Besides, increased P fertilisation has been implicated in environmental hazards such as the eutrophication of water supplies in developed countries (Hash *et al*., 2002).

Perhaps, a cheaper and more sustainable option for mitigating the effects of low soil P on sorghum yield is the application of organic fertilisers such as manure, compost and plant residues. While these have been shown to increase P levels in soils, the amount of P in organic fertilisers is highly variable and often insufficient to meet crop requirements (Risse *et al*., 2006). Moreover, the use of organic fertilisers on small-scale farms is constrained by unavailability of manure (where livestock is not a major component of the farming system) and the removal of plant residue at harvest for use as dry season fodder and building material (Verde and Matusso, 2014).

Widespread soil-P deficiency, dwindling rock phosphate reserves, high cost, unavailability and inefficient use of fertilisers strongly suggest that a more integrated approach is necessary to improve sorghum yield in West Africa. A more sustainable approach is the development of P-use efficient varieties. Until recently, research on improving sorghum adaptation to P deficiency has been minimal (Leiser *et al*., 2012). One of the main obstacles to breeding for P-use efficiency in sorghum was the limited degree of diversity for the trait (Ribaut and Poland, 2000). Recently, Leiser *et al*. (2014) reported sufficient genetic variability for P use-efficiency among West African

University of Ghana http://ugspace.ug.edu.gh

inbred lines and landraces. However, given the alarming decline in soil fertility and its associated low sorghum productivity in West Africa as well as the extremely diverse levels of P deficiency in sorghum-growing regions, there is a need to broaden the gene pool for phosphorus-use efficiency (PUE) in sorghum and breed for higher levels of the trait in the crop (Chianu *et al*., 2012; Gemenet *et al*., 2016). The challenge for breeders is to increase the genetic variability for PUE in sorghum, followed by selection of desirable phenotypes in low-P soils and the subsequent introgression of these cultivars into elite Africa lines.

While methods such as hybridisation, genetic engineering and somaclonal variation are available for increasing genetic diversity in crops, artificial mutagenesis offers an efficient and rapid means of generating new genotypes with desirable traits (Xin *et al*., 2008). Such genotypes may then be released either as direct mutants or used as parents in recombinant breeding programmes (Ahloowalia *et al*., 2004). According to the International Atomic Energy Agency, artificial mutagenesis has been used for the development of over 2000 new crop varieties with improved tolerance to several biotic and abiotic stresses (Ahloowalia *et al*., 2004). The main strategy in this case is the mutagenic treatment of elite genotypes followed by selection for morphological and/or physiological characters that influence the trait of interest (Parentoni and Souza, 2008; Sweeney *et al*., 2011).

Thus, this project seeks to identify and develop new P use-efficient sorghum genotypes through induced mutagenesis of the in-bred line BTx623. The availability and cultivation of such genotypes is likely to contribute to improving yields in the P-stressed and low-input cropping environments in West Africa. In turn, food security and livelihood of smallholder sorghum farmers may be improved. The cultivation of P use-efficient sorghum cultivars may reduce excessive fertiliser

University of Ghana http://ugspace.ug.edu.gh

application in high-input cropping systems. Thus, the goal of this project was to improve genetic variation for phosphorus-use efficiency in sorghum via induced mutagenesis.

The specific objectives were to;

1. determine farmers' production constraints, perceptions of soil fertility and preference for sorghum traits in the Upper East Region of Ghana,
2. assess the genetic variability within a chemically-mutagenised sorghum population at M_3 and
3. identify phosphorus-use efficient mutants within the population (at M_6).

University of Ghana http://ugspace.ug.edu.gh

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Origin domestication and distribution of sorghum

Sorghum is an ancient crop; it is thought to have diverged from a common ancestor as maize (Smith and Frederiksen, 2000; Paterson *et al*., 2004). According to Singh and Jauhar (2006), it was consumed by hunters and gatherers as early as 8000 B.C. Although some reports suggest diverse origin, archaeological evidence indicates that sorghum originated in north-eastern Africa (de Wet *et al*., 1967). Cultivated sorghum originated from wild races of *sorghum bicolor ssp. verticilliflorum* in the Ethiopian highlands as recently as 1000 BC (Kimber, 2000; Harlan, 1972). This is supported by the fact that the largest diversity of cultivated sorghum and several closely-related wild species can be found in this region presently (Bhattacharya *et al*., 2011). Thus, Ethiopia is generally accepted as the primary centre of origin (Vavilov, 1992).

It is likely that wild sorghum was domesticated through natural and deliberate selection for specific traits (Doggett, 1970; Kimber, 2000). Domestication may also have resulted from crosses between wild and cultivated types (House, 1985). This process resulted in gradual changes in several plant characteristics including seed size as well as the transformation of open inflorescence into compact types (House, 1985). These new types may have spread to eastern and southern Africa through the migration of the Bantu people (Westengen *et al*., 2014). Subsequently, the crop became adapted to a wide range of environments on the continent. Smith and Frederiksen (2000) suggest that this movement, genetic adaptation and inter-crossing in the isolated ecosystems of Africa gave rise to the five basic races of cultivated sorghum.

From Africa, sorghum spread to the Middle East, the Far East and India; considerable evidence exists of sorghum cultivation in India more than 4,500 years ago (Vavilov, 1992). Thus today,

University of Ghana http://ugspace.ug.edu.gh

India is regarded as the secondary centre of origin of the crop. Sorghum is relatively new to South America and Australia and was introduced to the USA in the middle of the 19th century (1857) through slave trade (Doggett, 1965b). Today, a diverse range of genotypes are cultivated in tropical and subtropical regions of the world (Legwaila *et al*., 2003). This includes several countries in the Americas, Asia, Oceania and Africa. Its cultivation in Europe however is limited to a few areas in Italy, France and Spain (Wang *et al*., 2014).

2.2 Classification of sorghum

Sorghum was first described by Linnaeus in 1753 under the name *Holcus*. He described three species of cultivated sorghum as *Holcus sorghum*, *Holcus saccaratus* and *Holcus bicolor* (House, 1985). In 1794, the genus *Sorghum* was separated from *Holcus* by Moench (House, 1978). Over time, the crop has been re-described by many taxonomists. However, the most definitive description was provided by Snowden, who classified sorghum into 52 species composed of 31 cultivated, 17 wild and 4 weedy species (Snowden, 1935). These species were later combined into a single species on the basis of the absence of genetic barriers (de Wet and Huckabay, 1967). The species now includes all cultivated sorghums as well as related semi-domesticated plants (de Wet, 1978). The *Sorghum* genus is further divided into five taxonomic sub-generic sections: *Eu-Sorghum*, *Chaetosorghum*, *Heterosorghum*, *Para-Sorghum* and *Stiposorghum* (Garber, 1950). All cultivated varieties and landraces belong to the sub-generic section *Eu-Sorghum* (Lazarides *et al*., 1991). Presently, the genus consists of 25 species (USDA-ARS, 2012). The scientific name for all cultivated sorghums is *Sorghum bicolor* (L.) Moench; Clayton and Renvoize, (1986) classified sorghum as follows;

Kingdom – *Plantae*

University of Ghana http://ugspace.ug.edu.gh

Sub-kingdom – *Tracheobionta*
Super-division – *Spermatophyta*
Division – *Magnoliophyta*
Class – *Liliopsida*
Sub-class – *Commelinidae*
Order – *Cyperales*
Family – *Poaceae*
Tribe – *Andropogonae*
Sub-tribe – *Sorghinae*
Genus – *Sorghum*
Species – *Sorghum bicolor*

The species is divided into 5 races and 10 intermediate races under *S. bicolor* spp. *bicolor* (de Wet and Harlan, 1970). These races include *bicolor, caudatum, kafir, durra* and *guinea* which are distinguishable by panicle morphology (Harlan and de Wet, 1972). The predominantly West African *Guinea*, is characterised by glabrous panicles and open sessile spikelets (Harlan, 1972). The *kafir*, found primarily in East and southern Africa is characterised by semi-compact panicles with hairy, sessile spikelets. Panicles of the *Caudatum* race (found in east Nigeria and eastern Sudan) are dense or slightly open with obovate to elliptical sessile spikelets while the *Durra* race (dominant in Ethiopia and Central Africa) is characterised by obovate panicles. The most diverse and primitive race, *bicolor* is characterised by open panicles and pedicellate, persistent spikelets (Smith and Frederiksen, 2000).

Like maize, sorghum has a haploid chromosome number of 10 (2n = 2x = 20) (Fedorov, 1969). The sorghum genome is small [approximately 730 Mbp] (Paterson, 2009). Its genome is approximately 60% larger than that of rice, 25% the size of the maize genome and 20 times smaller than that of wheat (Arumuganathan and Earle, 1991; Peterson *et al*., 2002). This makes it an ideal model for studying the structure and function of other cereal genomes (Paterson *et al*., 2004). The

University of Ghana http://ugspace.ug.edu.gh

ancestral linkage between sorghum and other cereals also provides insights into genome evolution (Bowers *et al*., 2005).

2.3 Sorghum production

Presently, total area under sorghum cultivation is estimated at 42 million hectares (FAO, 2014). Approximately 80% of this is located in developing countries in Asia and Africa (Christiaensen *et al*., 2010). In Africa, cultivation of the crop extends from the Atlantic coast to the borders of the Sahara and more arid parts of eastern and southern Africa (Wang *et al*., 2014). Sorghum acreage within sub-Saharan Africa is an estimated 24.8 million hectares, corresponding to 53% of the world's production area (FAO, 2012). The largest areas under cultivation in Africa are located in Nigeria, Sudan and Ethiopia (FAO, 2013). Other major sorghum-cultivating countries in Africa are Burkina Faso, Senegal, Tanzania, Mali, Cameroun and Ghana. In Ghana, it is cultivated on approximately 243, 000 ha of land (Addai and Alimiyawo, 2015).

The world produces a total of 59.3 million metric tonnes annually (FAO, 2014). The USA is currently the world's largest producer with an estimated 15 million tonnes per annum (FAOSTAT, 2015). In general, sorghum productivity in Africa has increased steadily over the decades from 11.6 million tonnes in 1976 to 20.9 million tonnes in 2009 (Atokple, 2010). However, this improvement in productivity has been attributed to increases in acreage and not in average yields on farmers' fields (FAO, 2010). Currently, Africa produces about a third of the world crop, an annual average of 26 million tonnes (FAOSTAT, 2015). Nigeria, Africa's largest producer, contributes an average of 6.1 million tonnes yearly (FAOSTAT, 2015). Ghana ranks 22nd in the world in terms of sorghum production (USDA, 2012). Most of country's sorghum is cultivated in the three northern regions mainly as a subsistence crop by smallholder farmers with land holdings

University of Ghana http://ugspace.ug.edu.gh

of less than 2 hectares (Kudadjie *et al*., 2004; Atokple, 2012). In Ghana, as is the case in several parts of West Africa, the crop is usually planted as sole stands or under irregular cropping systems (Ncube *et al*., 2007).

Average yields in the United States and Europe are estimated at 4.5 and 5 tonnes/ha respectively (Dahlberg *et al*., 2011). In Africa, average yields vary considerably at regional and national levels. For instance, productivity in West and Central Africa is an estimated 1.8 tonnes/ha compared to 2.5 tonnes/ha in East and Southern Africa (Wang *et al*., 2014). Yield in farmers' fields may be as low as 1 tonne/ha in Mali or as high as 2.8 tonnes/ha in South Africa (Leiser *et al*., 2014). Although Ghana has a yield potential of 2 to 3 tonnes /ha, average yield usually ranges from 700 to 900 kg/ha in the Upper East and Upper West Regions to higher values of 1200 kg/ha in Northern Region (Atokple, 2010).

2.4 Uses of sorghum

In developed regions of the world, sorghum is used primarily as feed for beef and dairy cattle, poultry and pigs (Berenji and Dahlberg, 2004). Sweet sorghums, due to their high sugar and biomass yield are used extensively for biofuel production in countries such as the USA and India (Shoemaker and Bransby, 2010). Other industrial uses of sweet sorghums include the production of sugar and syrup from the juice in stalks (Srinivasa Rao *et al*., 2012). Sorghum bagasse may also be used as feedstock for generation of electricity (Berenji and Dahlberg, 2004).

In Africa, sorghum is a very important source of food (Kudadjie *et al*., 2004). Traditionally, it is processed into a wide variety of foods such as thin and stiff porridges, bread and couscous (Kudadjie-Freeman and Dankyi-Boateng, 2012). Sorghum grains are nutritious and constitute a principal source of energy for many of Africa's rural poor (Thompson, 2000; Zohary and Hopf,

University of Ghana http://ugspace.ug.edu.gh

2000). Red-grain varieties are an excellent source of antioxidants (Klopfenstein and Hoseney, 1995; Chung *et al*., 1998). More recently, sorghum grain has been recommended for diabetics due to its slowly-digested starch and has gained attention as a substitute for wheat in the production of gluten-free food products (Rai *et al*., 2014; Dahlberg *et al*., 2011).

Sorghum plays an important role in the socio-economic development of many African rural folk (Kudadjie *et al*., 2004). For instance, it is the grain of choice for brewing traditional beers - an important income-earning activity for many rural women, as is the case in northern Ghana (Kudadjie *et al*., 2004). In Nigeria, sorghum grain is used as a substitute for barley in the industrial brewing of lager beer thereby offering income for growers and providing additional jobs in the value chain (Goode and Arendt, 2003). Although stover is typically used as dry season fodder, fencing material and thatch, it may also be used in small-scale production of brooms, mats and baskets (ICRISAT, 2006). In most parts of Africa, its use as biofuel crop is still emerging (Deenanath *et al*., 2012). However, in countries such as South Africa, the sorghum bioethanol industry is quite advanced and provides income for farmers (Mokhema, 2013). Due to its untapped potential as an industrial crop, the World Bank has tagged sorghum cultivation as one of the strategies for improving the lives of vulnerable people in Africa (Angelucci, 2013).

2.5 Edaphic and nutrient requirements of sorghum

Sorghum tolerates a diverse range of soils from heavy clays to medium loams (El-Bassam, 2010). Although it can be productive on shallow sandy soils, its yield is optimised on deep, well-drained loamy soils with high organic matter content; poorly-drained and compact soils may restrict root growth and overall performance (Verheye, 2010). Its growth and development is also influenced by soil pH (Butchee *et al*., 2012). Crop performance is best in soils with a pH between 6.0 and 6.5.

University of Ghana http://ugspace.ug.edu.gh

(Doggett, 1970). However, sorghum appears to be more tolerant to soil acidity and alkalinity compared to maize and other grain crops (Undersander, 2003). Nevertheless, in acid soils with pH below 4.7, root growth and overall plant growth may be severely constrained (Kidd and Proctor, 2001; Menezes *et al*., 2014). Under such conditions, liming is recommended to improve nutrient solubility and availability, while the application of acidifying fertilisers may improve growth in alkaline soils (Tan *et al*., 1991). Sorghum is moderately-tolerant to salinity; it is more tolerant than maize, wheat and rice but less tolerant than barley (Prasad and Staggenborg, 2009). Thus, it could be considered as an alternative crop in salt-stressed soils (de Lacerda *et al*., 2005). However, a high accumulation of salts such as sodium calcium and magnesium particularly during germination and early vegetative stage may severely limit germination and primary root growth (Oliveira *et al*., 2011).

An adequate supply of nutrients is necessary for plant establishment and growth. Nutrient application rates for sorghum differ according to climate, cultivar, soil type, amount of residual nutrients in the soil, target yield and cropping sequence (Daba and Zewedie, 2001; Kumar *et al*., 2011). As is the case with most plants, nitrogen is required in large quantities and is essential for vigorous growth and maximum yield. It may be applied to the crop in organic forms (manures and compost) or in inorganic forms such as urea, di-ammonium phosphate, ammonium nitrate, calcium nitrate or sodium nitrate (Tucker, 1999). Its availability is most critical from the 5-leaf to flowering stage (Rose *et al*., 2013). An inadequate supply of nitrogen may reduce leaf size and quality, delay crop maturity and affect seed development (Roy *et al*., 2005).

Potassium (K) is critical for optimum photosynthesis and the activation of enzymes (Roy *et al*., 2005). In sorghum, maximum uptake of K occurs during the early growth stages; thus, application at sowing is recommended particularly for fields with less than 150 kg K_2O per hectare and in

University of Ghana http://ugspace.ug.edu.gh

cropping systems where all plant residue is removed at harvest (Curt *et al*., 1995). A top-dressing may be applied 20 to 30 days after sowing under severe conditions of K deficiency (Agropedia, 2009). An optimum supply of potassium improves disease and pest resistance, water balance and stalk strength in the crop (Smith and Frederiksen, 2000).

Critical soil P values for sorghum are slightly less than maize and half that of wheat, indicating the relatively high uptake-efficiency of the crop (Gemenet *et al*., 2016). However, significant amounts of P are required throughout growth; from the seed germination and establishment to grain filling (Young and Long, 2000; Gelli *et al*., 2014). P application is most critical in soils with less than 5 mg P/kg available P and may be necessary in alfisols than in vertisols (El-Swaify *et al*., 1985; Sahrawat *et al*., 1996). Phosphorus should be applied at sowing typically by furrow placement or side dressing (Agropedia, 2009). An adequate supply of P promotes seedling establishment, root formation, flowering and maturation of grain which translates into higher biomass and grain yield (Bolland and Baker, 1988).

The most important climatic factors for optimum sorghum growth includes rainfall and temperature (Konate, 1984). In West Africa, sorghum is cultivated in the humid/sub-humid Guinea-savannah, semi-arid Sudan-savannah and arid Sudano-Sahelian zones which vary widely in rainfall distribution (Leiser *et al*., 2012). While acceptable yields can be produced with limited moisture, maximum yield requires a moisture distribution of about 600 to 700 mm particularly during the reproductive stage (Prasad and Staggenborg, 2009). Interestingly, the crop is also more tolerant to periodic flooding compared to maize (Borell *et al*., 2000).

Warm temperatures such as between 21^{o}C and 35^{o}C are required for seedling germination and establishment whereas temperatures between 26^{o}C to 34^{o}C are necessary for vegetative growth

University of Ghana http://ugspace.ug.edu.gh

and reproductive development (Tiryaki and Andrews, 2001; Alagarswamy and Ritchie 1991; Prassad *et al*., 2006a).

2.6. Phosphorus in soils

2.6.1 Forms of phosphorus in soils

Soil phosphorus exists in two main forms; inorganic and organic (Hansen *et al*., 2004). Organic soil P occurs in plant residues, manures and microbial organisms (Kwabiah *et al*., 2003). Its amount in soils can vary widely from 20 to 80% of total soil P (Holford, 1997). It may be present as stabilised forms such as inositol phosphates and phosphonates or active forms such as orthophosphate diesters and organic polyphosphates (Turner *et al*., 2002). Organic P is released to plants via mineralisation processes mediated by soil organisms and plant roots (Buresh and Smithson, 1997). To a large extent, availability of organic P to plants is affected by the rate of microbial conversion to available forms (orthophosphates) rather than its total amount (Richardson, 1994). Mineralisation processes in turn are highly influenced by soil moisture, temperature and pH (Turner *et al*., 2007).

Inorganic forms of P in soil consist of hydrous sesquioxides, aluminium and iron compounds in acidic soils and calcium compounds in alkaline, calcareous soils (Gahoonia *et al*., 1992). Inorganic pools are derived mainly through the dissolution of apatite and other primary P minerals and the mineralisation of soil organic matter (Buresh and Smithson, 1997). The form of inorganic P in solution is influenced largely by soil pH (Furihata *et al*., 1992). The primary orthophosphate ion ($H_2PO_4^-$) is more predominant in acid soils (below pH 6) whereas the secondary orthophosphate (HPO_4^{2-}) is predominant in alkaline soils (Condron *et al*., 2005). However, both forms are present in approximately equal proportion at neutral pH. The various forms of P have notable differences

University of Ghana http://ugspace.ug.edu.gh

in chemical behaviour, mobility and availability in soils (Reddy and DeLaune, 2008). Transformations between inorganic and organic P forms occur continuously to maintain equilibrium conditions (Tiecher *et al*., 2012).

2.6.2 Phosphorus availability and its acquisition by plants

Only 1 to 5% of total soil P occurs in plant-available forms (Molla *et al*., 1984). Thus, although total P in fertile soils may exceed plant requirements, its availability to plants may be severely restricted (Shen *et al*., 2011). P availability in soils is extremely complex and involves several physical, chemical and biological processes (Fink *et al*., 2016). It may be described in two broad contexts; spatial availability and bioavailability (Shen *et al*.., 2011). Bioavailability of P is linked to the concentration of soluble or dissolved forms of P present in soil for plant uptake (Hinsinger, 2001). It is influenced by several factors including mineralogy, composition and rate of hydrolysis of organic matter (Marschner, 1995). To a large extent, it is also influenced by the rate of adsorption and desorption of phosphates which in turn is highly affected by soil pH, composition of soil solution, the degree of weathering, drainage potential of the soil and clay fraction (Schaefer *et al*., 2008). For instance, P adsorption is significantly higher in clay loam soils than in sandy soils (Hinsinger, 1998). Similarly, P adsorption is less at slightly acidic to neutral pH than in extremely acidic and alkaline soils (Reddy and DeLaune, 2008). In acid soils, P is severely adsorbed by oxides and hydroxides of aluminium and iron, forming insoluble complexes such as strengite [$FePO_4.2H_2O$] and variscite [$AlPO_4.2H_2O$]) (Fairhurst *et al*., 1999). In neutral and alkaline soils, P is also likely to form stable complexes with calcium or magnesium (Devau *et al*., 2010). In parts of West Africa, P sorption rates can be as high as 405 mg P/kg leading to low

University of Ghana http://ugspace.ug.edu.gh

bioavailability of P (Bationo *et al*., 2003). According to Leiser *et al*., (2012), available P may be as low as 2 mg P/kg in some sorghum-growing areas.

Spatial availability of P on the other hand refers to the presence of sufficient amounts of soluble P within the rhizosphere for plant acquisition (Hinsinger, 1998). Due to its low mobility in soil, P stocks within the rhizosphere may be depleted (Marschner, 1995). This may be worsened by low soil moisture content, high temperature, aeration and compaction (Hash *et al*., 2002). Spatial availability of P may be improved by the placement of fertilisers within the effective rhizosphere or its slow diffusion from bulk soil to the rhizosphere (Lynch, 1995).

P is absorbed by plants as inorganic phosphate ions $H_2PO_4^-$ or HPO_4^{2-} (Hinsinger, 1998). Due to the steep concentration gradient (created by the low concentrations of P ions in soil solution and its high concentrations in root cells), uptake across the plasma membrane of root epidermal and cortical cells requires high-affinity active transport systems mediated by H^+ co-transporters (Shin *et al*., 2004). Upon acquisition, P is loaded into the xylem and translocated upward into shoots where it plays structural, biochemical and physiological roles in plant growth and development (Ai *et al*., 2009). This includes its involvement in metabolic processes such as photosynthesis, respiration, glycolysis, enzyme activation, membrane synthesis and stability (Schachtman *et al*., 1998). Within plants, P occurs as sugar phosphates in the cytoplasm, phospholipids in chloroplasts, chlorophyll and plant hormones, inorganic phosphates in the vacuole and as phytin in seeds (Tucker, 1999). The major function of phosphorus is in energy storage and transfer as it is an essential component of the energy molecule adenosine triphosphate (ATP). It is also an integral component of nucleic acids; phosphate groups link DNA or RNA molecules, thus form the backbone of nucleic acids (Shen *et al*., 2011).

University of Ghana http://ugspace.ug.edu.gh

2.6.3 Phosphorus status of West African soils

The available P content of cultivated soils in developed countries exceeds critical amounts required for plant growth (Melese *et al*., 2015). On the other hand, West African soils are typically vertisols, entisols, alfisols or inceptisols which are low in available P, highly-weathered, light-textured and highly-saturated with cations (Kang, 1985; Bationo and Mokwuenye, 1991; Gemenet *et al*., 2016). The low P status of West African soils can be attributed to two main factors. First is the geologic origin or the parent material from which these soils are derived (Fink *et al*., 2016). Due to a low occurrence of phosphate-bearing rocks such as apatite, strengite and variscite in the region, soils are derived mainly from rocks of low P content (van Kauwenbergh, 2006). Thus, West African soils are inherently P deficient. For instance, approximately 80% of soils in northern Ghana are formed from acidic parent material with low P availability of 8 mg kg^{-1} (Braimoh and Vlek, 2004).

The second cause of West Africa's low P status is nutrient depletion (Shepherd and Soule, 1998). In most cropping systems, nutrient output generally exceeds input resulting in a negative nutrient balance (Bationo *et al*., 2012). Soil nutrients are lost through erosion, leaching, burning of cover vegetation and the removal of crop residues at harvest (Kisinyo *et al*., 2012). In the last 30 years, an estimated 15 million tonnes of P has been lost from cultivated soils in Africa (Smaling, 1993). Bationo *et al*., (2012) reports that an average of 75 kg P ha^{-1} is lost annually from soils in several African countries. This situation is not limited to West Africa as annual depletion rates exceed 6.6 kg P ha-1 in Eastern African countries such as Kenya, Ethiopia and Rwanda (Smaling *et al*., 1997). Unlike nitrogen, P replenishment is mainly fertiliser dependent (Nziguheba, 2007). Unfortunately, such soil enhancement interventions are scarce in smallholder systems and nutrient replenishment depends to a large extent on the slow mineralization of rocks and minimum recycling of organic matter (Verde and Matusso, 2014).

University of Ghana http://ugspace.ug.edu.gh

2.7 Effect of phosphorus deficiency on sorghum productivity in West Africa

Soil P deficiency has been established as one of the main constraints to sorghum production (Gemenet *et al*., 2016). Its negative effect on seedling vigour, plant height, grain and stover yield has been documented in Burkina Faso, Mali and Ghana (Bationo *et al*., 2012, Leiser *et al*., 2015). When deficiency is mild, clearly recognisable symptoms may be absent. However, plants often appear stunted and exhibit a general lack of vigour (Sanginga and Woomer, 2009). On the other hand, severe P deficiency results in delayed maturity, marked reductions in overall growth and leaf size, with plants appearing spindly with dark green leaves (Katyal and Das, 1993). In certain varieties, leaves turn brown resulting in poor radiation interception and consequently sub-optimal rates of photosynthesis and carbon assimilation (Smalberger *et al*., 2006). Perhaps, the most-recognisable symptom of P deficiency in sorghum is the development of reddish-purple colouring on leaf sheaths as a result of the accumulation of anthocyanin (Grundon *et al*., 1986). The degree of purpling may vary from cultivar to cultivar but typically, red overtones appear first on leaf tips and margins of older leaves and progress towards the midrib and the full length of the blade (Sanginga and Woomer, 2009). Low soil P reduces grain filling, seed size and tillering and has also been shown to increase disease pressure on sorghum fields (Wall *et al*., 1994; Jones *et al*., 2003). For instance, the production and exudation of strigolactones for the parasitic weed *Striga* is enhanced in low P soils resulting in serious yield losses (Yoneyama *et al*., 2007). P deficiency symptoms are exacerbated by the marked reduction in crop response to N (Zhao *et al*., 2007). When P and N deficiency occur simultaneously, chlorophyll content is reduced and leaves appear pale green.

University of Ghana http://ugspace.ug.edu.gh

2.8 Crop adaptation to soil P deficiency

Plant adaptation mechanisms to soil P deficiency are based on acquisition, translocation, storage and utilisation of P (Ciarelli *et al*., 1998). The two main adaptation strategies are those that enhance P acquisition from surrounding soil (P acquisition efficiency) and those that improve physiological use of internal P [P utilisation efficiency] (Vance, 2001). Phosphorus Acquisition efficiency (PAE) is defined as the total P in the above-ground tissue at maturity per unit area while P utilisation efficiency (PutE) is the grain yield per unit of acquired P (Wang *et al*., 2010).

Mechanisms of improved uptake are probably more beneficial in soils rich in total P than in deficient soils (Rose *et al*., 2013). Such mechanisms are aimed at maximizing exploration of surrounding soil for continuous uptake (Lynch and Ho, 2005). These include alterations in root architecture, morphology and distribution patterns (Liao *et al*., 2001; Shen *et al*., 2011). For instance, under P-deficient conditions, some plant species may exhibit increases in root/shoot ratio, root hair formation, root branching and elongation (Shen *et al*., 2011). For example, white lupin (*Lupinus albus*) and Arabidopsis (*Arabidopsis thaliana*) plants may develop a denser cluster of roots under conditions of low P stress thereby facilitating effective exploration of soil (Vance, 2001). Similar increases in root/shoot ratio are observed in the common bean (*Phaseolus vulgaris*) under low P stress (Lynch and Brown, 2008). An increase in the number and length of lateral roots and root hairs have been observed in wheat, barley, maize and Arabidopsis (Zhu and Lynch, 2004). Due to the relative immobility of P in soils and its abundance in top layers, modifications in branching such as a more horizontal growth angle may also enhance topsoil foraging of P (Hodge *et al*., 2009). This phenomenon has been observed in P-efficient genotypes of common bean and maize (Lynch and Brown, 2008).

University of Ghana http://ugspace.ug.edu.gh

Another common adaptation of plants under soil P starvation is mycorrhizal symbioses (Brundrett, 2009). Such associations can improve P uptake by extending the nutrient absorptive area via the formation of hyphae or mycelia (Harrison, 2005). Differences in responsiveness to mycorrhizal inoculation under low P conditions can distinguish between P-use efficient genotypes and non-efficient ones (Feddermann *et al*., 2010). Raju *et al*. (1990) reports that in sorghum, symbiosis with vesicular-arbuscular mycorrhiza (VAM) resulted in increases in root length and a corresponding increase in P uptake. This is in contrast to reports by Leiser *et al*. (2016) which suggest that sorghum showed no positive relationship between VAM colonisation and grain yield. Kaeppler *et al*. (2000) suggest that symbiotic P acquisition may be more beneficial under severely low P conditions and less in fertile soils.

Apart from alterations in morphology and architecture, P uptake may be improved through root-induced biochemical changes (Shen *et al*., 2011). The synthesis and exudation of compounds such as low molecular weight organic acids (LMWOA), carboxylates, phosphatases and phytases in the rhizosphere play an essential role in enhancing the availability of soil P and hence its uptake (Marschner, 1995; Zhang *et al*., 2010). For instance, LMWOA reduce the pH of alkaline soils thereby enhancing the dissolution of soluble P minerals (Marschner, 1995). Carboxylates such as citrate, malate and oxalate increase P availability by mobilising inorganic P from precipitated forms through ligand exchange and chelation of Al, Fe and Ca while phosphatases enhance greater mobilisation of organic P through enzyme-catalysed hydrolysis (Vance, 2001). Such changes are reported in rice and sorghum variety SC 283 in which roots produce citrate that complexes with Al and enhance the dissolution of P fixed by Al in acid soils (Magalhaes, 2007).

While improved P acquisition in low P soils is undoubtedly beneficial in increasing yields, some have argued that such mechanisms are likely to cause further P depletion in cultivated soils (Lynch,

University of Ghana http://ugspace.ug.edu.gh

2007; Veneklaas *et al*., 2012). This argument is based on the existing imbalance between P fertilisation and its uptake/removal in small-scale farming systems (Rose *et al*., 2013). Thus, some authors suggest that a more efficient utilisation of internal P will ensure that limited P resources are channeled into producing higher yields (Veneklaas *et al*., 2012; Gemenet *et al*., 2016). It has also been suggested that breeding for internal P use-efficiency would be more relevant to the low input systems of West Africa. Arguably, due to declining root growth during reproductive stages, an efficient utilisation of internal P for grain development may be more valuable than the amount of P available for uptake (Rose *et al*., 2008). Efficient utilisation of internal P includes the production of the maximum amount of grain with the smallest accumulation of the nutrient (Moll *et al*., 1982). Efficient internal utilisation of P may also be defined as increased growth per unit of acquired P (Schachtman *et al*., 1998). The activation of these mechanisms in low P soils may differentiate between P-efficient and inefficient genotypes (Lynch and Brown, 2006). Further research is required to explain the physiological factors that contribute to improved utilisation of internal P in low P soils.

2.8 Strategies for improving sorghum productivity in low P soils

2.8.1 Traditional management strategies

Several measures have been adopted to improve agricultural productivity on low P soils (Kaizzi *et al*., 2007). Key among these is the application of organic and inorganic fertilisers (Maerere *et al*., 2001; Verde and Matusso, 2014). Inorganic P fertilisers available in West Africa (though on a limited scale) include single super phosphate (SSP), triple super phosphate (TSP), diammonium phosphate (DAP) and rock phosphate (Nekesa *et al*., 2005). The advantage of these inorganic sources of P in improving crop yield is their immediate availability for plant uptake and use (Verde

University of Ghana http://ugspace.ug.edu.gh

and Matusso, 2014). Nevertheless, organic fertilisers such as crop residues, green manures, compost and animal manures are also useful in enhancing crop performance in low P soils as have been demonstrated in many smallholder farms in Nigeria, Burkina Faso and Ghana (Mwangi *et al*., 2002; Odedina *et al*., 2011).

Unfortunately, the use of fertilisers as a strategy for improving sorghum production in low P soils in West Africa is constrained by several factors. Perhaps, the most important factor is the high cost of fertilisers, farmers' inability to afford the commodity and lack of access to credit (Leiser *et al*., 2015). Also, in West Africa, mineral fertilisers may be unavailable in rural areas due to lack of infrastructure, inefficient distribution systems and lack of fertiliser management policies (Chianu *et al*., 2012). Given that affordability and access to mineral fertiliser remain a challenge for smallholder farmers, many policies encourage the use of organic nutrient sources (Chianu *et al*., 2012). However, as is the case of mineral fertilisers, manure and compost are often unavailable in situations where livestock production is not intensive or a main component of the farming system (Parentoni *et al*., 2008). In arid parts of West Africa for instance, plant residues are more likely to be removed at harvest for use as dry season fodder than as a soil enhancement strategy (Lynch, 2007). Even when available, the P content of organic matter is highly variable and often insufficient to meet crop requirements (Risse *et al*., 2006). Furthermore, the impact of fertilisers on crop productivity in smallholder farms is diminished by farmers' low literacy levels and lack of information leading to improper application rates and placement methods (Buresh and Smithson, 1997). Thus, a large proportion of added P is lost through volatilisation and run-off leading to expensive annual applications (Driessen *et al*., 2000). Perhaps the greatest concern associated with P fertilisation is the rapid depletion of rock phosphate reserves and the potential phosphate crisis (Vance, 2001). Prices of P fertilisers are expected to increase with depleting

University of Ghana http://ugspace.ug.edu.gh

reserves and increasing demand; this is expected to make the commodity even more inaccessible to smallholder farmers in West Africa (Cordell *et al*., 2009). Lastly, fertiliser is seldom applied to traditional crops such as sorghum as is the case in many parts of West Africa; the introduction of fertiliser subsidies has had little effect on the fertilisation of the crop (Chianu *et al*., 2012).

In order to improve sorghum productivity on marginal soils in West Africa, fertiliser-use by small-scale, resource-poor farmers must be complemented with other approaches. Proposed strategies include improved crop-livestock integration for manure production, crop-tree-livestock integration to reduce erosion and provide green manure and the extraction of P from urban waste water (Zomer *et al*., 2009; Bayala *et al*., 2013). Another proven, environmentally-friendly and relatively inexpensive approach is the development of P use-efficient varieties (Lynch, 2007). This strategy is beneficial in two ways; it is likely to increase productivity in the low input systems in West Africa while encouraging a reduction in fertiliser use in high input systems without compromises in yield (Weaver and Wong, 2011).

2.8.2 Breeding strategies

2.8.2.1 Conventional approaches to breeding for phosphorus-use efficiency

Phosphorus use efficiency (PUE) is defined as the amount of biomass (stover and grain) produced per unit of available P in the soil (Moll *et al*., 1982). Rose *et al*. (2013) defined PUE as the grain yield per unit of P fertiliser applied or the grain yield per unit of P in the aboveground biomass. The concept of PUE has been reported in rice, maize, wheat and sorghum (Holford *et al*., 1997; Duan *et al*., 2007).

In Africa, breeding for PUE in sorghum, although limited, has been approached mainly through the use of conventional methods such as pedigree selection, backcrossing and population

University of Ghana http://ugspace.ug.edu.gh

improvement (Maqbool *et al*., 2001). Usually, such studies aim at identifying genotypes that produce acceptable yields under limited P conditions followed by crossing selected genotypes with sensitive ones (Gemenet *et al*., 2016). Conventional breeding employs two main strategies; Selection based on overall performance (grain yield and/or biomass) in low P soils or selection for phenotypic traits associated with P-use efficiency (Rose *et al*., 2013). Performance-based selections involve rigorous screening of genotypes on P-deficient and/or high P soils to reveal genetic variations in crop response (grain yield and biomass) (Quijano-Guerta *et al*., 2002). This has been suggested as one of the best predictors of genotypic variation for PUE and is based on the premise that certain genotypes produce similar yield under both low and high P conditions (Rao, 2001; Schaffert *et al*., 2001). In Mali, this method was used by Leiser *et al*. (2015) to identify P use-efficient sorghum genotypes among West African sorghum. The challenge of such phenotypic selections is for breeders to determine whether selections should be conducted under the conditions of low P (direct selection) or high P (indirect selection) (Gemenet *et al*., 2016). There have been contrasting reports on the efficacy of direct selection methods as opposed to indirect methods (Gemenet *et al*., 2016). While some researchers suggest that indirect selection in high P soils are likely to provide higher heritability estimates, others suggest that evaluations under low P stress are more likely to reveal P use-efficient genotypes (Banzinger and Cooper, 2001; Leiser *et al*., 2012). However, Banziger *et al*. (1997) reports that genotypes selected under low P stress may not be responsive to P fertilisation. Thus, Gallais and Coque (2006) recommended selection under P conditions that do not reduce yield beyond 40%.

Alternatively, breeding for PUE may be approached indirectly through the assessment morphological characters associated with the trait. These include plant height, leaf area, stem thickness, percent dry matter, amount of P partitioned to stover and grain and the degree of

University of Ghana http://ugspace.ug.edu.gh

exudation of P- mobilizing compounds (Sinclair, 1998; Broadley *et al*., 2007). The most-evaluated morphological traits are those associated with root architecture and morphology such as the ability to produce denser or more branched roots in P-depleted soils (Marschner, 1995; Kamara *et al*., 2003). Extensive genetic variation has been observed in sorghum root systems under low P stress, suggesting the critical role of roots in sorghum adaptation to low P soils (Jordan *et al*., 1979). However, the main challenge in evaluating root architecture and morphology in breeding work is the requirement for detailed analyses of root systems and rhizosphere interactions (Kondo *et al*., 2003). This usually involves destructive sampling or removal of the entire intact root system from the soil which may be impractical under field conditions. Also, many root traits have low heritability and are affected by environmental factors such as soil type and water availability, both of which are difficult to control in the field (Hash *et al*., 2002). Thus, although root evaluations may suit the low-cost nature of African breeding programmes, this form of selection must be used with caution (Hash *et al*., 2002).

Some conventional breeding programmes for PUE in sorghum have attempted selections based on genotypic variations in the level of VAM association (Hash *et al*., 2002). However, according to Hash *et al*., 2002), breeding for improved VAM association in sorghum was not effective in enhancing its adaptation to low P soils as variations in VAM colonisation did not significantly improve P uptake and yield in low P soils. Besides, such experiments are limited by variations in quantities of the fungi in soil and difficulties in inoculating plant roots (Vance, 2001). It is also difficult to evaluate the contribution of the fungi to P uptake compared to uptake by the plant's own root system (Hash *et al*., 2002).

While these forms of selection are straightforward, they require the development of near-isogenic lines which may take several years of backcrossing (Guo *et al*., 2009). Another major disadvantage

University of Ghana http://ugspace.ug.edu.gh

of these forms of selection is the tedious testing in multi-environments and the irregular distribution of P across field plots (Leiser *et al*., 2015). The heterogeneous availability of P in field plots may result in low heritability or the masking of genetic effects by experimental effects (Wissuwa *et al*., 2001). Thus, Kaeppler *et al*., (2000) suggest the use of controlled conditions such as pots, lysimeters and hydroponic systems as substitutes for field conditions. However, these require huge investments in equipment and screening procedures may not closely mimic or represent normal field conditions (Hash *et al*., 2002). According to Leiser *et al*. (2015), soil heterogeneity in field trials may be accounted for by spatial adjustments and the use of mixed models in data analysis to increase precision and reveal the extent of genotype x phosphorus interaction (Leiser *et al*., 2015).

2.8.2.2 Molecular approaches to breeding for phosphorus-use efficiency

Due to the limitations of sole phenotypic selections, genomic tools such as marker-assisted selection (MAS) have been proposed for breeding for PUE. MAS can increase the precision of selection under field conditions and hasten the breeding process by facilitating the choice of parental lines and reducing the need for costly multi-locational screening (Hash *et al*., 2002; Wissuwa *et al*., 2016). However, the use of MAS in breeding for improved PUE in sorghum depends on the identification and validation of genes or quantitative trait loci (QTL) associated with the trait (Gelli *et al*., 2014; Gemenet *et al*., 2016). Although the genetic basis of PUE traits is complex, the completion of the sorghum genome has provided new avenues for elucidating gene function in the crop (Paterson *et al*., 2009). Upon identification, these genes or genomic regions may be isolated and their expression manipulated to improve P-use efficiency in the crop (Crawford and Forde, 2002). Attempts to identify genes or QTLs associated with PUE in sorghum include work by Koegel *et al*. (2013) who identified two genes (SbAMT3; 1 and SbAMT4) coding

University of Ghana http://ugspace.ug.edu.gh

for ammonium transporters that were found to positively influence P uptake. The most important QTL for P- acquisition efficiency however, 'Phosphorus Uptake 1' (*PUP-1*) was mapped on chromosome 12 in the rice variety Kasalath (Wissuwa *et al*., 1998; 2002). The major gene Phosphorus Starvation Tolerance 1 - *PSTOL1* which promotes early root development, thus improving uptake and grain yield in low P soils was identified in the *PUP 1* (Gamuyao *et al*., 2012). Subsequently, other QTLS associated with tolerance to low P have reported in pearl millet and maize (Gemenet *et al*., 2016). QTL have also been identified for other PUE traits such as dry weight of shoots, tiller number (in wheat), leaf area and chlorophyll content in grains (in maize) (Su *et al*., 2006; Cai *et al*., 2012). The identification of these QTL and genes in sorghum followed by their introgression into elite African lines holds huge promise for developing P use-efficient African sorghum varieties.

2.8.2.3 Induced mutagenesis as an alternative breeding approach

Both conventional and molecular approaches in plant breeding require the availability of sufficient levels of genetic variation for the desired trait (Gemenet *et al*., 2016). A large variation for PUE exists among crop species; for instance, wheat, white lupin, maize, rice and barley differ widely in their levels of PUE (Hammond *et al*., 2009). More recently, significant levels of genetic variation for PUE has been reported among West African sorghums (Leiser *et al*., 2015; Gemenet *et al*., 2016). Their work showed Guinea-race genotypes to be more uptake-efficient whereas Caudatum-based ones were more utilisation-efficient. It has been suggested, that a combination of these two sources of germplasm may be necessary to develop a superior genotype that exhibits both uptake and utilisation efficiencies in low P environments (Gemenet *et al*., 2016). Whilst this is entirely possible, it may require several years of backcrossing and the development of recombinant inbred lines. Hybridisation may also be hampered by undesirable linkage drag and in some cases

University of Ghana http://ugspace.ug.edu.gh

incompatibility of the selected parents (Acquaah, 2015). Additionally, given that a substantial proportion of applied fertiliser is not acquired by plants, there still exists a significant margin for improving P acquisition in the crop (Hash *et al*., 2002). In West Africa, where fertilisation of traditional crops such as sorghum is almost non-existent, the availability of a more diverse genetic base for PUE in the crop is likely to be beneficial (Doumbia *et al*., 1993).

In addition to hybridisation, several methods are available for increasing genetic diversity in crops. These include genetic engineering and induced mutagenesis. Artificial mutagenesis offers a highly useful method for expanding or broadening the gene pool of any cultivated species (Dillon *et al*., 2007). Its primary role in plant breeding is the generation of hitherto unavailable alleles (Sikora *et al*., 2011). One of its key advantages over hybridisation is its ability to introduce random changes throughout the genome, resulting in a wide variety of mutations in target genes whereas hybridisation exploits existing variability within crop species for the development of new individuals by creating new combinations of existing traits (Sikora *et al*., 2011). Compared to transgenic methods, artificial mutagenesis can be readily exploited without regulatory restrictions (Parry *et al*., 2009).

Artificial mutagenesis may be achieved through the use of physical mutagens such as gamma rays, x-rays and UV light or chemical mutagens such as sodium azide, methylnitrosourea (MNU) and ethyl methanesulphonate (EMS) (Kodym and Afza, 2003). The main advantage of chemical mutagens is that they often result in single-nucleotide polymorphisms (SNPs) rather than deletions and translocations that are typical of radiological methods (Sikora *et al*., 2011). EMS is widely-used for seed-propagated crops due to its potential for producing a relatively high density of irreversible mutations (nucleotide substitution) (Talebi *et al*., 2012). This mutagen typically results in random point mutations (GC to AT base-pair transitions) by the alkylation of guanine bases

University of Ghana http://ugspace.ug.edu.gh

which subsequently causes the replacement of cytosine with thymine by DNA-polymerase (Till *et al*., 2007). It has been shown to be highly mutagenic in sorghum and optimized protocols are readily available in published reports (Xin *et al*., 2008).

The use of artificial mutagenesis for the improvement of tolerance to abiotic stresses such as drought and salinity have been reported in cereals (Brar and Jain, 1998). For example, increased tolerance to aluminium and low P stress via mutagenic treatments have been reported in Brazilian and Chilean wheat respectively (Camargo *et al*., 1995). Some 15 induced sorghum mutant accessions with tolerance to various biotic and abiotic stresses have been registered according to the International Atomic Energy Agency database (http://www-mvd.iaea.org/MVD/default.htm). Given that the availability of a genotype which possesses both uptake and utilisation efficiencies is beneficial for West Africa, this work is an attempt to identify new sources of both traits in sorghum (Gemenet *et al*., 2016). If successful, those genotypes may be used either directly as new varieties or as parents in recombinant breeding programmes. The approach is to increase the genetic variability for PUE in the crop through the use of artificial mutagenesis followed by the selection of desirable mutants in multi-locational trials.

University of Ghana http://ugspace.ug.edu.gh

CHAPTER THREE

3.0 FARMERS' PRODUCTION CONSTRAINTS, PERCEPTIONS OF SOIL FERTILITY AND PREFERENCE FOR SORGHUM TRAITS

3.1 Introduction

Ninety percent of Ghana's sorghum is cultivated in the three northern regions (Upper East, Upper West and Northern Regions) mainly as a rain-fed crop by subsistence farmers (RUDEMA, 2006). Its importance in these regions cannot be over-emphasized. Sorghum grains are an important food staple for many rural folk and are used in the preparation of several local beverages (Kudadjie *et al*., 2006). More recently, sorghum grains have been used as a substitute for barley in industrial breweries, allowing local farmers to earn additional income and breweries to save foreign exchange (Angelucci, 2013). Stover may also be used as fodder, household fuel, and as raw material for roofing traditional homesteads (Kudadjie *et al*., 2004). Weaving baskets and mats from sorghum stover is also an important cottage industry for rural women (Kudadjie-Freeman and Dankyi-Boateng, 2012).

In spite of its importance, sorghum productivity in northern Ghana is extremely low; rarely exceeding 2 t/ha (Kombiok *et al*., 2012). For instance in the Upper East Region, annual yields are estimated at 700 kg/ha (Al-Hassan and Jatoe, 2002). According to FAO (2013), sorghum production in northern Ghana dropped from 287,069 tonnes in 2011 to 256,736 tonnes in 2013. Such low yields threaten the food security and livelihood of many of the regions' rural poor (Quaye, 2008).

Low sorghum yields can be attributed to factors such as drought, high incidence of diseases and pests, cultivation of inherently low-yielding varieties and low plant densities on farms (SARI, 1995; Braimoh and Vlek, 2006; Atokple, 2010). Another key constraint to sorghum production in

University of Ghana http://ugspace.ug.edu.gh

northern Ghana is widespread soil infertility (Kombiok *et al*., 2012). In view of this, several strategies have been proposed to increase crop productivity on marginal soils, key of which is the promotion of fertiliser use among smallholder farmers (SARI, 1995; Kombiok *et al*., 2012). However, in spite of persistent efforts, reports indicate weak demand and low fertiliser use among sorghum farmers in Ghana and Africa as a whole (IFDC, 2006; Bumb *et al*., 2011). This has largely been attributed to high cost of fertilisers and its unavailability on rural markets (Laube, 2012). However, even when fertilisers and subsidies are available, there have been difficulties in convincing smallholder farmers to apply fertiliser to the crop (MoFA, 2009; Rware *et al*., 2016). This suggests that other factors in addition to unaffordability and unavailability of fertilisers might influence farmers' attitudes towards its use.

Farmers' perceptions have been shown to influence their adoption of agricultural practices and technologies (Marenya *et al*., 2008; Fosu-Mensah *et al*., 2012; Ndamani and Watanabe, 2015). Studies in Kenya, Ethiopia and Nigeria for instance revealed that farmers' perceptions of soil fertility influenced their attitudes towards fertiliser use and other soil management strategies (Mairura *et al*., 2007; Moges and Holden, 2007; Baba, 2017). In Ghana, given persistent reports of low fertiliser use among sorghum farmers, there is a need to seek more information on farmers' perceptions of soil infertility as well as their preferred soil management strategies (MoFA, 2009). This information may provide more insight on farmers' attitudes towards sorghum fertilisation which in turn may guide stakeholders on the need or otherwise to prescribe alternative approaches to increasing sorghum productivity in low-input systems. Although similar studies have been conducted across West Africa, perceptions can be location-specific and may also depend on socio-economic status and cultural considerations of the target group (Mairura *et al*., 2007; Ndamani and

University of Ghana http://ugspace.ug.edu.gh

Watanabe, 2015; Yeshaneh, 2015). Thus, it is important to focus on assessing the perceptions of these farmers at the community level.

Additionally, a better understanding of the constraints to sorghum production from the farmers' perspective will enable stakeholders effectively prioritise and address constraints in the target areas. Also, an assessment of farmers' preference for traits will help scientists set relevant breeding goals and enhance the willingness of farmers to accept and use prescribed measures.

The role of participatory rural appraisal (PRA) is to facilitate a greater interaction between farmers and researchers and provide a platform for assessing farmers' indigenous knowledge and perceptions through semi-structured interviews and questionnaires (Theis and Grady, 1991; Chambers, 1992c).

The specific objectives of this study were to;

1. identify production constraints of smallholder sorghum farmers in the Upper East Region of Ghana,
2. determine farmers' perceptions of soil fertility,
3. identify farmers' soil management methods and
4. identify farmers' preferences for sorghum traits.

University of Ghana http://ugspace.ug.edu.gh

3.2 Materials and methods

3.2.1 Description of study sites

The study was conducted in four villages; Gbane and Yameriga in the Talensi-Nabdam district and Gumyoko and Tempelim in the Binduri district. Both districts are located in the Upper East region of Ghana (Lat. 10°15' and 10°10'N, Long. 0°and 1°4'W). The Talensi-Nabdam district lies between Latitude 10.15° and 10.60° north of the Equator and Longitude 0.31° and 10.5° (GSS, 2013). The topography is predominantly undulating, thus erosion-prone (Kpongor, 2007). Rainfall pattern is unimodal and unpredictable and is characterised by a short rainy season from May to October (annual mean of 950mm) followed by a long dry season of six to seven months. Temperatures are generally high (between 26°C and 45°C). Natural vegetation is guinea savannah woodland characterised by short scattered trees. Cultivated crops include sorghum, millet, rice and a range of legumes and vegetables (Kudajie-Freeman and Boateng, 2012). Soils here are generally alfisols which vary from light-textured sandy loams to heavier-textured soils (Kpongor, 2007). Soil pH ranges from 5.1 to 8.7, total nitrogen from 0.61 to 11.6 mg/kg soil while available phosphorus ranges from 1.75 to 14.75 mg/kg soil (Braimoh and Vlek, 2004).

Binduri is located between Latitudes 11° 11^1 and 10° 40^1 N and Longitudes 0° 18^1 W and 0° 6^1 E (GSS, 2013). The climate of Binduri is similar to that of Talensi-Nabdam, however, mean annual rainfall is lower (800 mm). Natural vegetation in Binduri district is mainly the Sahel Savannah type with scattered trees (GSS, 2013). Similar to Talensi-Nabdam, its topography is undulating. Thus, low-lying areas are prone to erosion. Soils here are generally of the savannah ochrosol type, ranging from sandy loams of good water retention capacities to clay loams (Kpongor, 2007). In both districts, sorghum is a major crop and it is grown mainly by small-scale and/or resource-poor

University of Ghana http://ugspace.ug.edu.gh

farmers. These districts were selected based on the importance of the crop as well as yield and socio-economic status. A geographical representation of the two districts is shown in Figure 3.1.

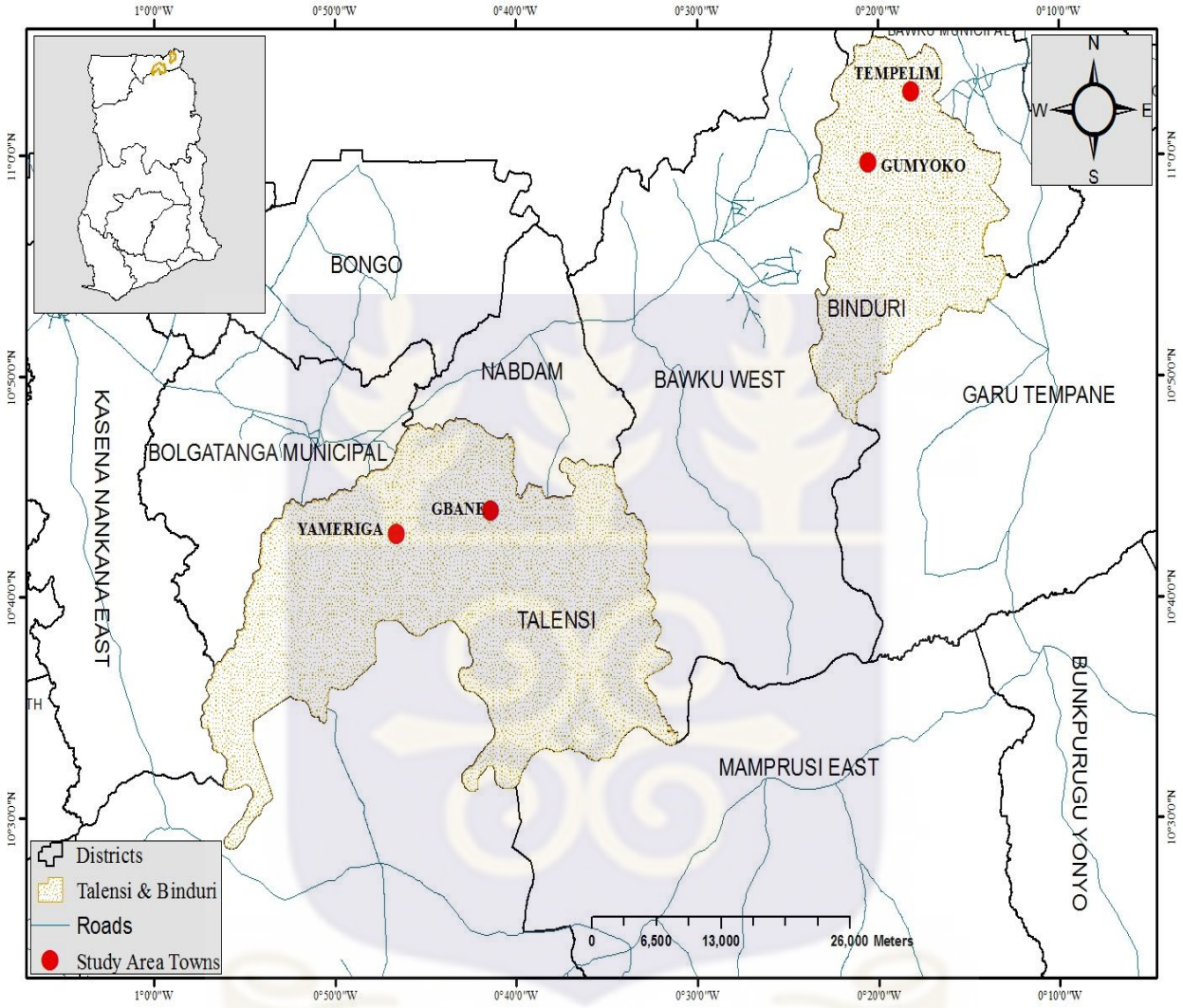


Figure 3.1. Geographical representation of Talensi-Nabdam and Binduri districts.

University of Ghana http://ugspace.ug.edu.gh

3.2.2 Sampling procedure and data collection techniques

Focused group discussions were organised with stakeholders (farmers, agricultural extension officers and researcher) at each village to obtain information on general constraints. One group was organised per village, each comprising a maximum of seven farmers including male and female representation. Subsequently, heads of households or available family members involved in farming activities were interviewed individually using semi-structured questionnaires (Appendix 1). The questionnaire comprised five sections with questions related to demographics, constraints to sorghum productivity, perceptions and assessment of soil fertility, fertiliser use and other soil management strategies and lastly, preferences for traits. Interviews were followed by visits to some sorghum fields during which direct observations were made. A total of 122 sorghum farmers were sampled in the two districts. The number of respondents that were sampled in each village is given in Table 3.1.

Table 3.1. Number of respondents across the study sites

Districts	Villages	Number of respondents
Talensi-Nabdam	Gbane	28
	Yameriga	32
Binduri	Gumyoko	32
	Templenim	30
Total		122

University of Ghana http://ugspace.ug.edu.gh

3.2.3 Data analysis

Data were summarized into averages and frequencies using XLSTAT 2012. Descriptive statistics, t-tests and chi-square tests were done using IBM Statistical Package for Social Sciences (SPSS) version 23.

3.3 Results

3.3.1 Demographic characteristics of households

Out of 122 farmers, 73 were male, representing approximately 60%. A male majority was the trend in all four communities. The highest percentage of female farmers (47%) was observed in Yameriga, compared to Gumyoko (44%), Tempelim (37%) and Gbane (32%) (Table 3.2.). In terms of number, there was no significant variation in gender across the communities. Farmers' age ranged from 25 to 75 years. Respondents belonged to three main religions; Christianity (41%), Islam (37%) and Traditional (22%). Overall, majority of respondents (57%) had no formal education, whilst the proportion of farmers with primary and secondary education was 32% and 8% respectively (Table-2). Only 3% of farmers had been educated to the tertiary level. The highest literacy levels were recorded in Gbane where 57.1% of respondents had at least basic education. This was followed by Yameriga (50%), Gumyoko (34.4%) and Tempelim (33.3%).

University of Ghana http://ugspace.ug.edu.gh

Table 3.2. Demographic characteristics of households

		Communities						
Variables	Characteristics	Gbane	Gumyoko	Tempelim	Yameriga	Total	Percentage	p - values
Gender	Male	19	18	19	17	73	59.8	0.643
	Female	9	14	11	15	49	40.2	
	Total	28	32	30	32	122	100.0	
Age (years)	<30	1	5	2	10	18	14.8	0.094
	31-45	15	13	14	12	54	44.3	
	46-60	10	11	11	5	37	30.3	
	>60	2	3	3	5	13	10.7	
	Total	28	32	30	32	122	100.0	
Religion	Christians	13	14	11	12	50	41.0	0.346
	Muslims	9	10	16	10	45	36.9	
	Traditionalists	6	8	3	10	27	22.1	
	Total	28	32	30	32	122	100.0	
Marital status	Married	25	31	26	20	102	83.6	0.002
	Single	2	1	4	12	19	15.6	
	Divorced	1	0	0	0	1	0.80	
	Total	28	32	30	32	122	100.0	
Number of children	No child	2	1	3	3	9	7.4	0.098
	1 to 5	14	23	8	19	64	52.5	
	6 to 10	7	6	14	6	33	27.0	
	11 to 15	5	1	4	4	14	11.5	
	>15	0	1	1	0	2	1.6	
	Total	28	32	30	32	122	100.0	
Literacy level	None	12	21	20	16	69	56.6	0.373
	Basic education	12	9	7	11	39	32.0	
	Secondary	2	1	2	5	10	8.2	
	Tertiary	2	1	1	0	4	3.3	
	Total	28	32	30	32	122	100.0	

University of Ghana http://ugspace.ug.edu.gh

3.3.2 Socio-economic characteristics of households

The longest farming experience observed among the farmers was 36 years (Table 3.3). Thirty percent had been involved in farming for over 15 years. More than half (51%) had at least 11 years of farming experience. The highest percentage of experienced farmers (> 10 years) was recorded in Gbane (60.7%) and Tempelim (56.7%). Only 14% of the respondents had less than 5 years' experience in farming. Fifty five percent of farmers cultivated sorghum solely for household use (food and feed) whereas for 44% of farmers, the crop was cultivated as a source of food, feed and income. The farmers made an average income of $50 (224 cedis) from farming in the previous season.

University of Ghana http://ugspace.ug.edu.gh

Table 3.3. Socio-economic and farm characteristics of households

		Communities						
Variables	Characteristics	Gbane	Gumyoko	Tempelim	Yameriga	Total	Percentage	p -values
Farming as main occupation	Yes	28	32	20	32	112	91.8	0.000
	No	0	0	10	0	10	8.2	
	Total	28	32	30	32	122	100.0	
Farming experience (years)	≤5	0	8	3	6	17	13.9	0.248
	6 to 10	11	8	10	13	42	34.4	
	11 to 15	8	6	8	4	26	21.3	
	>15	9	10	9	9	37	30.3	
	Total	28	32	30	32	122	100.0	
Purpose for sorghum cultivation	Household use only	8	23	11	25	67	54.9	0.000
	Income only	0	1	0	0	1	0.8	
	Both	20	8	19	7	54	44.3	
	Total	28	32	30	32	122	100.0	
Number of varieties grown	One	6	13	9	8	36	29.5	0.059
	Two	12	15	19	16	62	50.8	
	Three	10	4	1	6	21	17.2	
	Four	0	0	1	2	3	2.5	
	Total	28	32	30	32	122	100.0	
Total farm size	<1 ha	17	14	5	9	45	36.9	0.006
	1 to 2 ha	9	17	22	23	71	58.2	
	3 to 4 ha	2	1	3	0	6	4.9	
	Total	28	32	30	32	122	100.0	
Area allocated to sorghum	< 1 ha	26	29	18	30	103	84.4	0.000
	1 to 2 ha	2	3	12	2	19	15.6	
	Total	28	32	30	32	122	100.0	

University of Ghana http://ugspace.ug.edu.gh

3.3.3. Farm size, area allocated to sorghum and estimated grain yield

A large majority (93%) of farmers owned their farm lands. A total of 163.7 ha of farmland was available for farming in the four communities; 78.89 ha of total land was allocated to sorghum production, representing 48.2% (Table 3.4). Overall, farm sizes varied from 0.2 ha to 4.86 ha, with an average of 1.34 ha. Farm sizes in Gbane ranged from 0.2 to 4.45 ha. In Yameriga farm lands ranged from 0.2 to 2.83 ha, whereas in Gumyoko and Tempelim, farm sizes ranged from 0.2 to 3.24 and 0.4 to 4.86 respectively. Details of farm sizes in the various communities are shown in Table 3.4. Almost 50% of total farm land was allocated to sorghum production in all the communities with the exception of Gbane where the proportion was 58%. By farmers' estimations, on the average, 471.9kg of grain was produced per hectare in the last growing season. Approximately 39% harvested less than 250 kg of grain, 48% harvested between 250 and 500 kg whereas 13% had a yield of between 550 and 700 kg. Sorghum productivity was highest in Gbane (606 kg/ha) and lowest in Tempelim (364 kg/ha). Gumyoko and Yameriga had average yields of 525 kg/ha and 450 kg/ha respectively.

University of Ghana http://ugspace.ug.edu.gh

Table 3.4. Farm size and area allocated to sorghum within the communities

District	Village	Number of respondents	Total farm size (ha)	Average farm size (ha)	Land allocated to sorghum (ha)	Average land allocated to sorghum (ha)	Proportion of land allocated to sorghum (%)
Talensi-Nabdam	Gbane	28	27.52	0.98	14.93	0.53	54.25
	Yameriga	32	40.87	1.28	19.27	0.60	47.14
Binduri	Gumyoko	32	40.27	1.26	20.09	0.63	49.88
	Tempelim	30	55.04	1.83	24.6	0.82	44.69
Total		122	163.7	1.34	78.89	0.65	48.19

University of Ghana http://ugspace.ug.edu.gh

3.3.4 Sources of seed and information

A large majority of farmers (72%) saved seeds from previous cropping seasons (Figure 3.2A). Some farmers (15%) purchased seed from the local market than from the MOFA office (11%) whereas a small minority (4%) obtained their seeds from relatives or colleagues. In general, information on improved cultivars, agronomic practices and technology was from more than one source. Seventy seven percent cited farmer associations and colleagues as major sources of information (Figure 3.2B). The Ministry of Agriculture through extension officers was also a major source of information (71%).

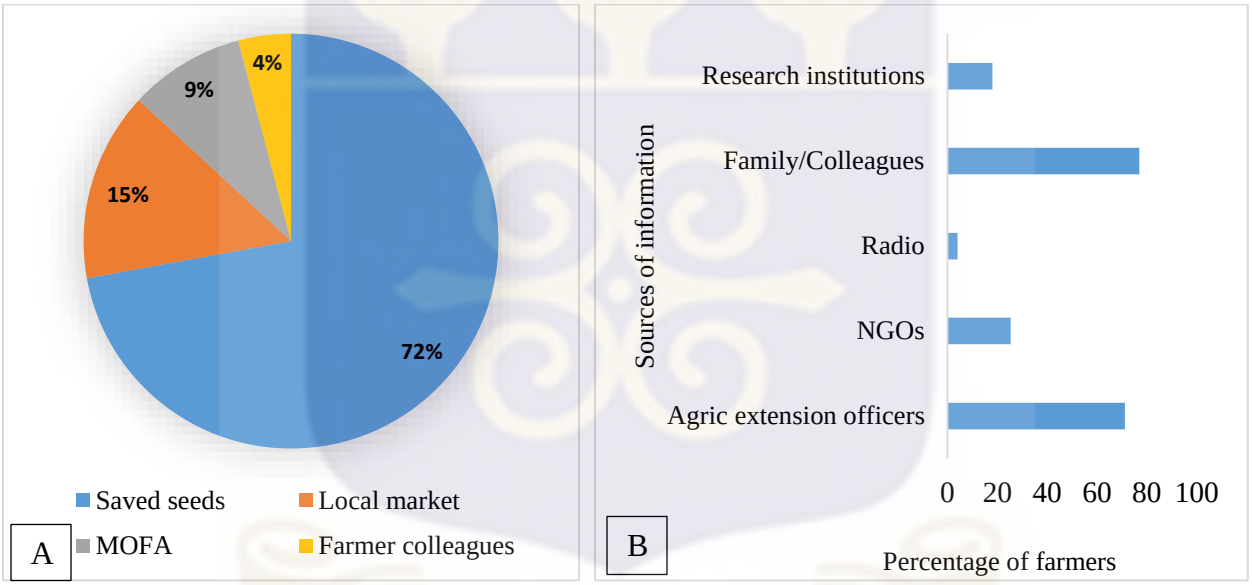


Figure 3.2. (A) Sources of seed (B) sources of information across the communities

University of Ghana http://ugspace.ug.edu.gh

3.3.5 General constraints to sorghum production

Eight major constraints to sorghum production were cited among the farmers in the two districts. They included drought, high cost of farming inputs (agro-chemicals, hired labour, tractors or oxen and seeds), declining soil fertility, *Striga*, diseases, post-harvest losses, land unavailability and pests (bird damage) [Table 3.5]. Overall, drought was the most important constraint whereas declining soil fertility was ranked third (Table 3.5). The trend for most important constraint (drought) remained the same within all the communities except Yameriga where high cost of farm input was the most important constraint. Declining soil fertility was ranked second in Gumyoko, fourth in Tempelim and Yameriga and fifth in Gbane (Table 3.5).

University of Ghana http://ugspace.ug.edu.gh

Table 3.5. Ranking of sorghum production constraints across the four communities

	Communities											
	Gbane		Gumyoko		Tempelim		Yameriga					
Major constraints	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Overall Means	Std. Dev	Overall Rank	p - values
Drought	1.6	1	2.2	1	1.8	1	2.6	2	1.59	0.44	1	0.003
Cost of farm input	3.2	2	2.8	3	2.6	2	2.4	1	2.58	0.35	2	0.001
Declining soil fertility	4.7	5	2.3	2	3.9	4	4.4	4	3.76	1.09	3	0.006
Striga infestation	4.3	4	4.7	4	5.6	5	3.7	3	4.45	0.80	4	0.001
Diseases	4.0	3	5.2	5	5.8	6	4.7	5	4.82	0.78	5	0.001
Post-harvest losses	4.8	6	6.8	8	3.2	3	5.4	6	5.31	1.48	6	0.006
Land unavailability	7.1	8	5.5	6	6.3	7	6.6	8	6.65	0.66	7	0.000
Pests (bird damage)	6.3	7	6.4	7	6.7	8	6.2	7	6.79	0.21	8	0.000

** The highest score is 1 and the lowest is 8.

University of Ghana http://ugspace.ug.edu.gh

3.3.6 Farmers' description and perception of soil fertility

More than half of farmers (51.6%) described their soils as moderately fertile (Table 3.6). Almost 42% described their soils as low in fertility whilst 6.6% described their soils as highly fertile. In general, farmers described fertile soils as darker, more compact and moist whereas infertile soils were described as stony, reddish or 'lighter' in colour and texture. The main criteria for assessment of soil fertility (88.5%) was colour (Table3.6). This was followed closely by crop performance (85%). Soil texture and high moisture retention were also cited as good indicators of soil health as indicated by 66% and 46% of farmers respectively. A small minority (13%) mentioned the presence of weeds and other plants as indicators of soil fertility.

A large majority (95%) perceived symptoms of nutrient-stress in sorghum as easily-recognisable. In this regard, the most-mentioned symptoms were poor yields (75%) and stunted growth (43%). A much lesser proportion mentioned delayed maturity (22%), poor seedling establishment (9.8%) and leaf discolorations (0.8%) as symptoms of nutrient-stress on sorghum. Sixty seven percent of farmers indicated that sorghum yield could be improved by fertiliser application (Table 3.7). However, only 38% of farmers applied fertiliser to the crop (Table 3.8).

The number of farmers who applied fertiliser to sorghum was highest in Gumyoko (63%) and lowest in Tempelim (20%). More farmers (43.5%) fertilised the crop with manure and/or household waste than with mineral fertilisers (23.9%). Almost 33% fertilised the crop with a combination of inorganic and organic fertilisers. The most frequently cited constraint (82%) to fertiliser use was farmers' inability to afford the commodity. A lesser proportion (48%) mentioned unavailability of fertiliser as a constraint.

University of Ghana http://ugspace.ug.edu.gh

Table 3.6. Farmers' description of soils

Variables	Characteristics	Gbane	Gumyoko	Tempelim	Yameriga	Total	Percentage	p - values
Description of soil	Highly fertile	4	0	1	3	8	6.6	0.008
	Moderately fertile	17	10	17	19	63	51.6	
	Poor	7	22	12	10	51	41.8	
	Total	28	32	30	32	122	100.0	
Crop performance	Yes	25	25	27	27	104	85.2	0.53
	No	3	7	3	5	18	14.8	
	Total	28	32	30	32	122	100.0	
Soil texture	Yes	20	26	16	19	81	66.4	0.09
	No	8	6	14	13	41	33.6	
	Total	28	32	30	32	122	100.0	
Soil moisture	Yes	15	16	14	11	56	45.9	0.458
	No	13	16	16	21	66	54.1	
	Total	28	32	30	32	122	100.0	
Soil colour	Yes	26	27	26	29	108	88.5	0.729
	No	2	5	4	3	14	11.5	
	Total	28	32	30	32	122	100.0	
Soil cover	Yes	8	4	1	3	16	13.1	0.032
	No	20	28	29	29	106	86.9	
	Total	28	32	30	32	122	100.0	

University of Ghana http://ugspace.ug.edu.gh

Table 3.7. Farmers' perceptions of soil fertility and its effect on sorghum

		Communities						
Variables	Characteristics	Gbane	Gumyoko	Tempelim	Yameriga	Total	Percentage	p-values
Is sorghum yield	Yes	23	21	18	20	82	67.2	0.273
improved by fertiliser	No	5	11	12	12	40	32.8	
	Total	28	32	30	32	122	100.0	
Is nutrient-stress	Yes	26	31	27	32	116	95.1	0.281
recognisable on sorghum	No	2	1	3	0	6	4.9	
	Total	28	32	30	32	122	100.0	
Stunted growth	Yes	22	29	15	25	91	74.6	0.002
	No	6	3	15	7	31	25.4	
	Total	28	32	30	32	122	100.0	
Reduced yield	Yes	14	8	14	17	53	43.4	0.099
	No	14	24	16	15	69	56.6	
	Total	28	32	30	32	122	100.0	
Delayed maturity	Yes	10	6	6	5	27	22.1	0.253
	No	18	26	24	27	95	77.9	
	Total	28	32	30	32	122	100.0	
Poor seedling establishment	Yes	3	3	2	4	12	9.8	0.89
	No	25	29	28	28	110	90.2	
	Total	28	32	30	32	122	100.0	
Leaf discolorations	Yes	1	0	0	0	1	0.8	0.336
	No	27	32	30	32	121	99.2	
	Total	28	32	30	32	122	100.0	

University of Ghana http://ugspace.ug.edu.gh

3.3.7 Farmers' cropping systems and soil management practices

Mono-cropping of sorghum was practiced by a 4% of farmers (Table 3.8). Seventy three percent of farmers typically cultivated the crop in variable mixed cropping systems with crops such as millet, soybean, groundnut, cowpea, bambara bean, okro and other vegetables. Twenty three percent indicated inter-cropping sorghum with millet and legumes as their main cropping system. Mixed cropping was highest in Yameriga (91%) and lowest in Gbane (54%). On the other hand, intercropping was highest in Gbane (36%) and lowest in Gumyoko (9%). No defined crop rotational system was mentioned by the farmers.

Shifting cultivation was not a common practice. Seventy five percent cultivated the crop on the same piece of land each season. With regard to other soil management practices, less than half (46%) retained some crop residue on harvested fields. This form of mulching was highest in Gbane (50%) and lowest in Tempelim (40%). At least one erosion control method was practiced by 60% of farmers. Stone bunding, earth bunding or grass strips were the main erosion control methods.

University of Ghana http://ugspace.ug.edu.gh

Table 3.8 Farmers' cropping systems and soil management practices

Variable	Characteristics	Gbane	Gumyoko	Tempelim	Yameriga	Total	Percentage	p-values
Cropping system	Mono-cropping	3	2	0	0	5	4.1	0.028
	Mixed cropping	15	21	24	29	89	73.0	
	Intercropping	10	9	6	3	28	23.0	
	Total	28	32	30	32	122	100.0	
Retention of crop residues	Yes	14	15	12	15	56	45.9	0.888
	No	14	17	18	17	66	54.1	
	Total	28	32	30	32	122	100.0	
Shifting cultivation	Yes	10	15	4	2	31	25.4	0.000
	No	18	17	26	30	91	74.6	
	Total	28	32	30	32	122	100.0	
Erosion control	Yes	24	18	12	19	73	59.8	0.005
	No	4	14	18	13	49	40.2	
	Total	28	32	30	32	122	100.0	
Application of fertilisers	Yes	13	20	6	7	46	37.7	0.001
	No	15	12	24	25	76	62.3	
	Total	28	32	30	32	122	100.0	
Type of fertiliser	Organic	6	6	5	3	20	43.5	0.000
	Inorganic	4	5	0	2	11	23.9	
	Both	3	9	1	2	15	32.6	
	Total	13	20	6	7	46	100.0	
Cost of fertiliser as a constraint	Yes	22	28	26	24	100	82.0	0.497
	No	6	4	4	8	22	18.0	
	Total	28	32	30	32	122	100.0	
Unavailability of fertiliser as a constraint	Yes	16	18	13	11	58	47.5	0.217
	No	12	14	17	21	64	52.5	
	Total	28	32	30	32	122	100.0	

University of Ghana http://ugspace.ug.edu.gh

3.3.8 Cultivated sorghum varieties and farmers' preference for traits

Farmers cultivated between two and ten different crops. Apart from sorghum, other cultivated crops included millet, rice, maize, groundnuts, soybean, cowpea, tomatoes, garden eggs and okro. Seven sorghum varieties, Naga Red, Belko-peleg, Belko-zia, Naga white, Kapaala, Dorado and Kowerig were recorded across the four communities. The highest number of sorghum varieties grown by a farmer was four (Table 3.3). Overall, the most-cultivated variety was Naga-red; as indicated by 66% of farmers (Figure 3.3). This was followed closely by Belko-peleg (64.8%). Belko zia, Naga white, Kapaala, Dorado and Kowerig varieties were cultivated by 53.3%, 31.2%, 28.7%, 13.9% and 9.8% respectively. In the Talensi-Nabdam district, the most-cultivated variety was Naga Red (73%). Belko-peleg was the most-cultivated variety in Binduri (66%).

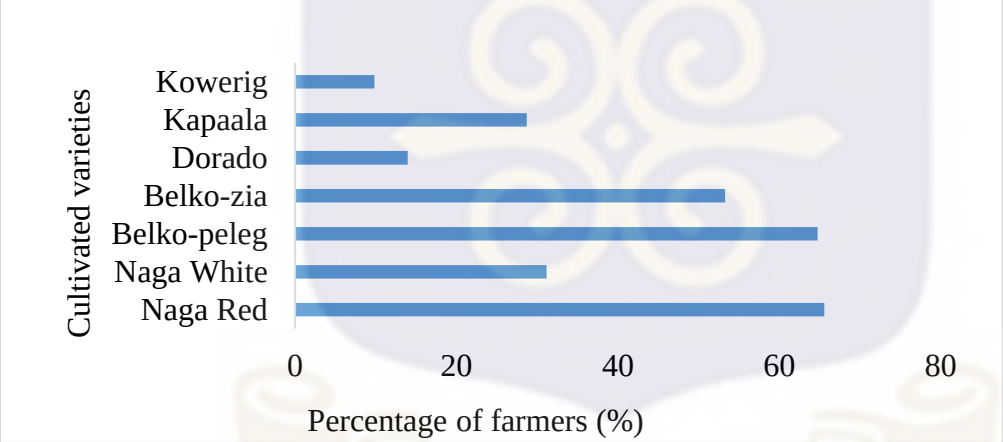


Figure 3.3. Diversity of sorghum varieties cultivated in the communities

Overall, drought tolerance was the most-preferred trait, followed by high grain yield and earliness (Table 3.9). Grain quality was the fourth most-preferred trait. These included all characteristics directly or indirectly linked to the grain such as taste, storage quality, suitability for food and beverage and threshability.

University of Ghana http://ugspace.ug.edu.gh

Crop adaptation to poor soils ranked fifth, ahead of disease tolerance and resistance to bird damage. At the community level, high grain yield was the most-preferred trait in Gbane and Gumyoko, whereas drought tolerance and earliness were the most-preferred traits in Tempelim and Yameriga respectively. Varieties with low fertiliser requirement ranked third in Gumyoko but fifth in all other communities.

University of Ghana http://ugspace.ug.edu.gh

Table 3.9. Ranking of farmers' preference for sorghum traits

	Communities											
	Gbane		Gumyoko		Tempelim		Yameriga					
Preference criteria	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Overall Mean	Std. Deviation	Rank	p-values
Drought tolerance	2.3	2	2.1	2	1.8	1	3.1	4	2.3	0.6	1	0.004
High grain yield	2.0	1	1.8	1	3.3	4	3.0	3	2.5	0.7	2	0.006
Early-maturing	3.1	3	3.9	5	2.8	2	2.0	1	3.0	0.8	3	0.005
Good grain quality	3.3	4	3.8	4	3.2	3	2.4	2	3.2	0.6	4	0.001
Low fertiliser requirement	5.7	5	3.7	3	4.2	5	5.4	5	4.8	1.0	5	0.002
Resistance to *Striga*	6.3	6	6.5	6	6.8	7	6.4	6	6.5	0.2	6	0.000
Disease tolerance	6.5	7	7.1	8	6.6	6	6.9	8	6.8	0.3	7	0.000
Tolerance to pests	6.9	8	6.7	7	7.1	8	6.7	7	6.9	0.2	8	0.000

** The highest score is 1 and the lowest is 8.

University of Ghana http://ugspace.ug.edu.gh

3.4 Discussion

In the surveyed communities, sorghum was cultivated more as a means of providing food for the household than as a source of income. Farmers indicated that income generation from sorghum was limited by poor yields and their inability to meet household food demand. This observation is corroborated by other surveys in northern Ghana (IFAD 2010; Eguavoen (2013). On the other hand, farmers derive income from sorghum either directly from the sale of grains or indirectly by brewing local beer. The farmers also rely on off-farm economic activities for additional income. For women, these include the sale of firewood and cooked food, gathering of fruit, cooked food and shea butter preparation whereas artisanship (auto-mechanic and blacksmithing) and employment as casual labourers are the main activities for men. For smallholders, off-farm activities are important strategies for minimizing food insecurity and improving livelihood (MoFA, 2015; Osarfo *et al*., 2016).

Farm sizes were generally below two hectares. However, almost half of cropped lands was allocated to sorghum cultivation, an indication of its importance in the communities (Kudadjie *et al*., 2004). The small farm sizes may be attributed to scarcity of arable land and/or high cost of renting additional land (Ohene-Yankyera, 2004). Also in the Upper East Region, as is the case in many parts of Ghana, farming is extremely labour-intensive with limited mechanisation (Diao *et al*., 2014). Thus, larger farms are likely to require the hiring of expensive casual labour, tractors or oxen, an investment many smallholder farmers may be unable to make (Whitehead, 2003).

Literacy levels were low among the farmers. According to Enu and Attah-Obeng (2013), lack of formal education is a hindrance to agricultural productivity in northern Ghana. Other reports also suggest that farmers with higher education often possess greater capabilities for assessing their environments and implementing technologies (Akinbile, 2003; Uematsu and Mishra, 2010). Thus,

University of Ghana http://ugspace.ug.edu.gh

it might be expected that the general lack of formal education among the farmers would be a barrier to effective assessment of soil fertility. On the contrary, the high experience levels among the farmers seemed to compensate for low literacy levels. For instance, most farmers described their soils with easily-observable indicators such as soil colour, texture and crop performance. They also recognized stunted growth and reduced yield as symptoms of nutrient stress in sorghum. In a similar study in Ethiopia, farmers also cited crop performance as one of the main criteria for assessing soil fertility (Yeshaneh, 2015). Although leaf discolorations and poor stand establishment were also cited as symptoms of nutrient-stress in sorghum, farmers associated these symptoms more with drought than with poor soils. This observation might be due to the fact that, both abiotic factors present similar symptoms (Chen *et al*., 2015). Moreover, nutrient unavailability is interrelated with drought as nutrient adsorption by plants is influenced by soil moisture content (Schoonover and Crim, 2015).

Seven sorghum varieties were identified in the communities. Due to differences in ethnicity and language, identical sorghum varieties were referred to by different vernacular names. For example, red-grained varieties were interchangeably referred to as *Kezie, Keto* or *Kimolga*, an observation that has also been reported in Ghana by Kudadjie *et al*., (2004) and in Benin by Missihoun *et al*., (2012). Preference for the Naga Red variety was clear with farmers citing its suitability for brewing local beer as a major incentive. Farmers also prefer Naga Red due to its early-maturing characteristic as it provides a less risky option for farmers in case of insufficient rain (Kudadjie-Freeman and Dankyi-Boateng (2012). The popularity of the late-maturing, low-yielding Belko-peleg within the communities is likely due to its suitability for preparing *tuo zaafi* and other local foods (Kudadjie *et al*., 2004). According to Buah *et al*., (2012), Naga white and Kapaala are

University of Ghana http://ugspace.ug.edu.gh

cultivated on a lesser scale due to farmers' perceptions of their higher fertiliser requirements, low grain quality and susceptibility to bird damage.

The most important sources of information for the farmers were family and friends. Some information was also received through extension officers, research institution and NGOs. Access to information on agricultural innovations has been shown to increase farm output in many rural parts of Africa (Kimaru-Muchai *et al*., 2012). However, informal channels of information such as observed among the farmers may expose them to the risks of inadequate or inaccurate information which is likely to hinder productivity (Benard *et al*., 2014). The impact of agricultural extension services was particularly obvious in Gbane where estimated sorghum productivity was highest. Electronic media such as radio and television were not important sources of information due to limited or no access to electricity.

Majority of the farmers save seeds for subsequent planting seasons, a frequent practice in northern Ghana and other parts of West Africa (Kudadjie-Freeman and Boateng, 2012; Dossou-Aminon *et al*., 2015). Although such seed systems have been practiced for decades, reports suggest that poor post-harvest handling of seeds as well as damage by pests may lead to poor plant establishment, a factor which may contribute to low yields among these farmers (Ochieng *et al*., 2011).

Sorghum yield among the farmers was low as evidenced by productivity estimates of 364 to 606 kg/ha). In the Upper East Region sorghum yield is estimated at 700 kg/ha (Alhassan and Jatoe, 2009). This observation suggests that food insecurity and low income are critical issues for many farm households in the surveyed districts. The poor yields observed in this study may be attributed to factors such as low plant densities on farmers' fields and the cultivation of inherently low-yielding varieties (Atokple, 2010). However, from the farmers' perspective, the major constraint

University of Ghana http://ugspace.ug.edu.gh

to sorghum productivity was drought. Drought has been reported to be one of the main constraints to crop productivity in northern Ghana (Ndamani and Watanabe, 2015). Given that crop is cultivated mainly under rain-fed conditions, the low and erratic rainfall patterns characteristic of this agro-ecological zone often exposes the crop to moisture stress leading to poor yields (Zougmore, 2003). The second most important constraint was high cost of farm inputs. Farmers described this mainly as cost of hiring tractors, oxen or labour for land preparation and maintenance. Farmers reiterated that limited access to ploughing services results in delays in sowing and limits farm sizes. Millar *et al*., (2007) report that although the use of tractors and bullocks for land preparation has increased in northern Ghana, the patronage of such services is limited by high cost. Similar observations have been made by Nin-Pratt and McBride (2014). The third major constraint was declining soil fertility. Soil nutrient levels in smallholder farms in West Africa are often extremely low as a result of deforestation, overgrazing and burning of cover vegetation (Mapfumo and Giller, 2001; Twomlow and Ncube, 2001; Henao and Baanante, 2006; Omotayo and Chukwuka, 2009). Farmers' approach to tackling the problem of declining soil fertility was mainly erosion control through methods such as stone bunding, earth bunding and vetiver grass strips. Soil erosion is severe in many parts of northern Ghana and farmers were quite knowledgeable of its effects and the benefits associated with its control (Veihe, 2002; EPA, 2003). This is most likely due to extension services by MOFA officers and other stakeholders. On the other hand, shifting cultivation and mulching were uncommon in the communities. Farmers cited increasing economic pressure as the main driving force. In recent times, land fallow as a conservation method is limited in many parts of West Africa, an observation that has been attributed to due to increasing population densities and escalating land pressure (Laube, 2007; Kanchebe, 2010). Also, the retention of plant residue at harvest (mulching) as a soil enhancement

University of Ghana http://ugspace.ug.edu.gh

method was low due to removal of stover for use as feed and household fuel. This practice is common in northern Ghana, particularly in the Upper East Region due to scarcity of grazing land and high population density (Kombiok *et al.*, 2012). The main cropping systems were mixed cropping and intercropping, cropping patterns which have been practiced for decades in northern Ghana (Diehl, 1992). Among smallholders, mixed cropping is usually an insurance against crop failure or as a strategy for providing a variety of food for the household (Eguavoen, 2013).

In general, farmers were aware of the role of fertilisers in enhancing sorghum yield. This is likely due to personal experiences, on-farm trials and/or demonstrations. However, fertiliser application was almost non-existent. The amount of applied fertiliser was not well-defined due difficulties in estimating quantities. However, the trend among smallholder sorghum farmers is the application of quantities far below recommended rates (Kombiok *et al*., 2012). Often, there is no deliberate fertilisation of sorghum and the crop most likely benefits from fertiliser applied to other crops in the mixed cropping system. According to the farmers, two main factors influence their attitude towards sorghum fertilisation. The most important was farmers' inability to afford fertiliser. This observation has been widely reported in Ghana and has been attributed to extreme poverty rates among farmers in the region (Yilma, 2006; Laube, 2007; Quaye, 2008; Abane, 2015). Access to government-subsidised fertiliser, which was the case for some of the farmers in this study had little impact on fertilisation of the crop. Unavailability of mineral fertilisers was a lesser problem with many reporting of sufficient quantities on local markets. On the other hand, farmers described unavailability in terms of late arrival of government-subsidised fertiliser. Application of manure and/or household waste to the crop was an alternative for some farmers. This form of soil fertilisation is common in northern Ghana (Gyasi and Uitto 1997; Issaka *et al*., 2016). Unfortunately, its use is constrained by insufficient quantities, laborious gathering from free-range

University of Ghana http://ugspace.ug.edu.gh

animals as well as its transportation to farmlands (Tossah, 2000). Thus, a combination of both organic and inorganic fertilisers was a more popular choice among the farmers. Although high cost of fertilisers and limited availability were the most cited constraints in this survey, other reviews suggest that farmers' perceptions of the crops' low response to applied fertiliser is a key impediment to its fertilisation (Kpongor, 2009; Kihara *et al*., 2016). In this study, 33% of farmers were of the perception that sorghum yield does not improve significantly with fertiliser application. Kombiok *et al*., (2012) suggests that such perceptions are due to the minimal yield increases farmers may observe when fertiliser is applied to local varieties. This perceived unprofitability is likely to influence farmers' attitude towards fertilising the crop (Nkegbe and Shankar 2014).

Tolerance to drought was identified as the most-preferred trait. In their survey of parts of northern Ghana, Ndamani and Watanabe (2015) suggest that although farmers recognize the effect of drought on crop production they often lack the capacity to implement adaptation practices. This may account for farmers' preference for drought-tolerant types. Preference for earliness in sorghum may be linked to lower risks of crop failure in case of insufficient rain and timely provision of food after the long dry season (Kombiok *et al*., 2012).

Qualities of the grain such as taste, storage quality, suitability for food and beverage, threshability and market value have been reported to be of importance to farmers (Kudadjie *et al*., 2004). Sorghum is widely consumed in northern Ghana

MacCarthy and Vlek, 2012). The fifth most-preferred trait was low fertiliser requirement. Low adoption of some improved sorghum varieties in northern Ghana has been linked to associated high fertiliser requirements (Buah *et al*., 2012). Thus, farmers are likely to recognize the need for this trait particularly due to their inability to afford mineral fertilisers.

University of Ghana http://ugspace.ug.edu.gh

3.5 Conclusions

Sorghum production in the sampled communities is faced with several constraints, the most important of which were drought, limited access to ploughing services and declining soil fertility. Farmers were cognizant of the effects of declining soil fertility on sorghum yield. However, application of fertiliser to the crop was low. High cost of mineral fertilisers, untimely access to the commodity and limited availability of organic nutrient sources were the most important constraints to fertiliser use. Farmers employed other soil management strategies such as erosion control through the use of stone and earth bunding. Mixed cropping of the sorghum with legumes and other food crops was the cropping system of choice. The most-preferred sorghum traits were drought tolerance, high grain yield, earliness, suitability of grain for food and beverages as well as varieties with low fertiliser requirements.

University of Ghana http://ugspace.ug.edu.gh

CHAPTER FOUR

PHENOTYPIC ANALYSES FOR IDENTIFICATION OF ARTIFICIALLY-INDUCED VARIABILITY IN SORGHUM

4.1 Introduction

Genetic diversity is a key component of plant breeding; to a large extent, the success of any breeding programme depends on the availability of sufficient levels of genetic variation for the trait of interest (Govindaraj *et al*., 2015; Gemenet *et al*., 2016). Over decades, plant breeders have relied on the natural or existing genetic variation within species for crop improvement (Wooten, 2001). Sorghum improvement programmes for instance, heavily exploit the existing variation within cultivated genotypes and/or their wild relatives (Chantereau *et al*., 2001). The main approach in these programmes has been hybridisation (Xu, 2010). Hybridisation, particularly of diverse parents, is highly-useful for expanding the genetic diversity within crop species, in that, several possible genotypes may be obtained (Breseghello, 2013; Schnell, 2015). However, modern hybridisation programmes usually focus on a relatively narrow gene pool resulting in a continuous recycling of genes within the species (Reddy *et al*., 2006). This, coupled with artificial selection during the breeding process has led to significant losses in diversity in sorghum (van Harten, 1998; Rakshit *et al*., 2012). The problem is worsened by the gradual replacement of landraces with high-yielding cultivars on farmers' fields (Breseghello, 2013; Dossou-Aminon *et al*., 2015).

Losses in genetic diversity may affect the crop's adaptation to environmental stresses (Phillips and Wolfe, 2005). This is of concern particularly in West Africa where farming environments are highly variable and often plagued by several biotic and abiotic stresses (Kong *et al*., 2000). More importantly, given the critical role that sorghum breeding plays in meeting food demand in West

University of Ghana http://ugspace.ug.edu.gh

Africa, any reduction in the genetic variability available to breeders threatens the food security of the region (Beresghello, 2013).

Besides hybridisation, genetic diversity of crops may be broadened through tissue culture (somaclonal variation), genetic engineering and mutagenesis (Larkin and Scowcroft, 1981, Ye *et al*., 2000; Xin *et al*., 2008). Unfortunately, somaclonal variation has not been routinely applied to sorghum and has also been reported to add little value for creating genetic variability in the crop (Omondi *et al*., 2013). Transgenic methods, although highly effective for introducing hitherto unavailable genes within species, are not readily-exploited in West Africa due to tedious biosafety regulatory restrictions and associated high cost (Henikoff and Comai, 2003). On the other hand, artificial mutagenesis is a readily-available and effective tool for generating germplasm with diverse characteristics (Dillon *et al*., 2007; Liang, 2009). The key advantage of mutagenesis over hybridisation is its ability to introduce random changes throughout the plant genome resulting in a wide variety of mutations in target genes whereas hybridisation is only effective in creating new combinations of existing alleles (House, 1995; Zhang *et al*., 2007). Mutagenesis is particularly beneficial when the genetic variability for any trait of interest is limited or non-existent in cultivated or wild genotypes (Rakszegi *et al*., 2010).

The technique has been successfully applied to cereals including rice, wheat, barley and maize (Ahloowalia *et al*., 2004; Caldwell *et al*., 2004; Till *et al*., 2004b; Suzuki *et al*., 2008). These mutant varieties exhibit a wide array of improved traits such as resistance to blast, yellow mottle virus and *Striga asiatica* as well as tolerance to acidity, drought and salinity (Jenks *et al*., 1994; Kiruki *et al*., 2006; Peters *et al*., 2009). In sorghum, the method was used to increase genetic variability for lysine content as well as develop multi-seeded and nuclear male sterile genotypes (Axtell *et al*., 1979; Xin *et al*., 2017).

University of Ghana http://ugspace.ug.edu.gh

Subsequent to mutagenic treatment, assessment of the mutagenised population for any induced variability is necessary to confirm its usefulness or otherwise as a germplasm resource (Xin *et al*., 2008). This may be achieved through morphological characterisation which is a relatively simple, inexpensive and efficient method (Rakshit *et al*., 2012; Elangovan *et al*., 2013). Morphological characterisation provides an opportunity for studying the performance of the mutagenised lines under actual growing conditions which in turn facilitates the identification of desirable genotypes (van Beuningen and Busch, 1997; Elangovan *et al*., 2014). For mutant populations, characterisation over several generations also helps validate the stability of any altered traits (Luz *et al*., 2016). Subsequently, desirable genotypes be released either directly as new mutant varieties or used as parents in recombinant breeding programmes (Ahloowalia, 2004; Xin *et al*., 2008).

Thus, the goal of this study was to enhance genetic variability for agro-morphological traits in sorghum through artificial mutagenesis. The specific objectives were to;

1. assess a chemically-mutagenised population for any induced genetic variability and
2. identify within this population putative mutants with desirable morpho-agronomic traits.

4.2 Materials and methods

4.2.1 Description of study site

The experiment was conducted during the 2013 cropping season at the research station of the University of Ghana, Legon (Latitude 5º36'N, Longitude 0º10W). The area lies within the Coastal Savannah agro-ecological zone. The natural vegetation is mainly grassland (short and medium grasses) interspersed with dense thickets and a few trees (EPA, 2003). Rainfall pattern in this area is bi-modal. There is a major rainy season from March to July and a minor rainy season from September to October. Annual average rainfall is approximately 800 mm with a range of 600 to

University of Ghana http://ugspace.ug.edu.gh

1200 mm (AQUATSAT, 2005). The average minimum and maximum temperatures are 22°C and 35°C respectively. The predominant soil type is well-drained Savannah Ochrosol (Ferric Acrisol) derived from quartzite schist, classified as the Haatso series (FAO, 1994).These are sandy loams, light in texture and inherently poor in fertility (Brammer, 1962). Rainfall and temperature conditions of the study site during the experimental period are shown in Table 4.1.

Table 4.1. Meteorological data for the sites during the study period

		Mean monthly temperature	
Month	Total monthly rainfall (mm)	Maximum (°C)	Minimum (°C)
May	130	31	23
June	210	29	23
July	50	28	22
August	30	28	22

Source: Ghana meteorological agency (2013)

4.2.2 Generation of mutagenised population

The mutagenised population was developed at and by the Whistler Agronomy Laboratory, Purdue University, USA. The mutagenised population was derived from mutagenic treatment of BTx623. Btx623 is a white-seeded inbred line developed and released in Texas in 1976 (Miller 1976). Its pedigree is BTx3197 x SC170. It is a widely-used maintainer line (B line) classified as a Kafir/Zera-Zera derivative (Menz *et al*., 2002). It is also the genotype selected for genome sequencing of the crop (Paterson *et al*., 2009).

Homogeneity of M_0 seeds was ensured by repeated selfing over six generations and selection by single seed descent as recommended by Xin *et al*., (2008). At each generation, seeds were selected from one plant that presented the most typical traits of BTx623. The mutagen used was ethyl methane sulphonate (EMS) [Sigma Aldrich, St Louis, MO]. Initial experiments were carried out to determine optimum concentration of EMS for mutagenesis. Subsequently, batches of 100g of dry seed (approximately 3300 seeds) were soaked in 200 ml of tap water containing EMS at a

University of Ghana http://ugspace.ug.edu.gh

concentration of 0.25% (v/v). The soaked seeds were maintained under continuous agitation for 16 hours at 50 revolutions per minute on rotary shaker. The treated seeds were then washed thoroughly in 400 ml of tap water for five hours at room temperature, changing the water every 30 minutes. They were then air-dried on tissue paper for 24 hours at room temperature.

Air dried seeds were planted in the field at high densities (120,000 seeds/hectare) to produce M_1 plants. Each fertile panicle was harvested manually and threshed individually for use as M_2 seeds which were then planted in head rows. Head rows were inspected closely for aberrant phenotypes in comparison to the wild type BTx623. M_2 head rows which showed two or more plants with altered and/or distinct phenotypes were tagged as putative mutants for further evaluation. Panicles from these tagged lines were harvested individually, threshed and advanced as M_3 seed. At each generation, panicles were bagged before anthesis with rain-proof paper pollination bags (Lawson Bags, Northfield, IL) to prevent cross pollination. M_3 seeds were stored in paper envelopes which were in turn stored in plastic containers at $^{-}20\ ^{o}C$.

The germplasm used in this study comprised a population of 547 of these mutagenised M_3 families. Three additional genotypes were used as controls; wildtype BTx623, Tx631 and Grinkan. Tx631 is a common grain sorghum line released in 1985 as a selection from the cross (BTx378 x SC110-9) x BTx615. Grinkan is a popular short-day and dwarf guinea-caudatum open-pollinated variety with intermediate maturity (Abdulai, 2012).

4.2.4 Experimental design and layout

The M_3 families were planted in an augmented design. Twenty nine blocks were planted in total. Each block comprised twenty two genotypes; nineteen putative mutant families and three control varieties planted randomly. Each genotype was planted in a single row plot of approximately 3

University of Ghana http://ugspace.ug.edu.gh

metres, using a planting distance of 0.3 metres within rows and 0.8 metres between rows. Ten hills were sown per family at 3 seeds per hill. Test plots were later thinned to one plant per hill. Plants were maintained mainly under rain-fed conditions. However, irrigation was applied when necessary. Fertilizer was applied at a rate of 60 kg N ha^{-1}, 30 kg/ha of phosphorus (P_2O_5) and 30 kg/ha potassium (K_2O) in two split doses; at three and six weeks after planting. Standard agronomic and plant protection (weed and insect control) measures were applied during the cropping season.

4.2.5 Data collection

Five plants were randomly-selected in each row and tagged. Data on nine quantitative traits were recorded at different growth stages. This included days to flowering (DTF), plant height (PH), number of leaves per plant (NL) and stem girth (SG) at anthesis. At maturity, panicles were harvested, air-dried for 2 weeks at ambient temperature and threshed. Data were then collected on panicle length (PL), peduncle exsertion (PE), panicle width (PW), hundred-seed weight (HSW) and grain yield per plant (GYP).

For qualitative traits, throughout the season, all plants in each family were closely-inspected for novel or distinct phenotypes in comparison to wild-type BTx623. Qualitative traits that were considered included leaf characteristics (size, arrangement, midrib colour, lesions and necrotic areas), plant size, tendency to tiller, tendency to wilt or senesce, the presence or absence of epicuticular wax on stems and threshability (freely threshable, partly threshable and difficult to thresh). All the mutagenised families were then categorised as described by Xin *et al*. (2008) and USDA mutant descriptors for sorghum (www.lbk.ars.usda.gov/psgd/sorghum/till/index.aspx).

University of Ghana http://ugspace.ug.edu.gh

4.2.6 Data analysis

Descriptive statistics were obtained using summary statistics procedure in XLSTAT 2017 (Addinsoft, Paris, France). A one-way analysis of variance (ANOVA) for each quantitative trait was performed. Where means were statistically significant ($p<0.05$), ANOVA was followed by mean separation using Dunnett's test ($p<0.05$) to determine which putative mutant families were significantly different from the control (BTx623).

Genetic parameters were then calculated to predict the extent of induced genetic variability. Genotypic and phenotypic variances ($\sigma 2g$ and $\sigma 2p$ respectively), genotypic coefficient of variation (GCV) and phenotypic coefficients of variation (PCV) were computed according to the formula proposed by Johnson et al. (1955). The coefficients were categorised as proposed by Khorgade *et al*. (1985) where values of less than 10%, 10 to 20% and greater than 20% were considered as low, intermediate and high respectively (Khorgade *et al*., 1985). The heritability was computed based on the methods given by Falconer (1960a). All computations were done using Microsoft Excel 2013.

Pearson's correlation coefficients (*r*) were calculated between the phenotypic traits to assess trait associations. The percentage contribution of each trait to total genetic variation was estimated by Principal Component Analysis (PCA) using the mean values of the nine quantitative traits. Cluster analysis was performed using Unweighted Pair Group Method with Arithmetic mean (UPGMA) was employed to determine the extent of heterogeneity induced within the population. These analyses were done using XLSTAT 2017 software (Addinsoft, Paris, France).

University of Ghana http://ugspace.ug.edu.gh

4.3. Results

4.3.1 Variation within the mutagenised population for quantitative traits

Highly significant differences ($p \leq 0.01$) were observed within the mutagenised population for all the studied quantitative traits (Table 4.3). Highly significant differences were also observed between several mutagenised families and the wildtype BTx623. Descriptive statistics, results of ANOVA and mean separation for each trait are elaborated below.

Number of days to anthesis ranged from 51 and 70 days. The earliest anthesis was observed in Mut2619 whereas the latest flowering (70 days) was observed in Mut0878. Seventy five M_3 families were significantly different ($p<0.01$) from BTx623. Of these, fifteen families were earlier than the wildtype whereas sixty reached anthesis later than the control variety.

Plant height ranged from 23 to 142 cm. The shortest families were Mut0992 and Mut2094#1, both of which recorded heights of less than 50 cm whereas Mut3053 presented the tallest plants. Compared to an average of 109.8 cm for the wild-type BTx623, 386 of the putative mutant families were significantly ($p < 0.01$) shorter than the control whereas ten M_3 families were significantly taller than the control.

Number of leaves per plant was least (7) in *Mut3057* and *Mut1668* and highest (12) in twelve M_3 families (Mut1504, Mut1505, Mut1457#1, Mut0755, Mut3809, Mut2716, Mut2811, Mut2807, Mut0931, Mut1884, Mut0561, Mut2039 and Mut2038#1). The wildtype BTx623 also presented an average of 12 leaves per plant. Compared to this, the number of leaves per plant was significantly reduced in twenty eight families. For all other families, the trait was not significantly different ($p<0.01$) from the control.

University of Ghana http://ugspace.ug.edu.gh

Stem girth was thinnest in Mut1668 and Mut3515-2 (7.3 and 12.6 mm respectively) and thickest (25.2 cm) in Mut2807. An average of 24.5 cm was observed by the wildtype. Compared to the average stem girth observed for the wildtype (24.5 cm), 359 families were significantly thinner. There were no putative mutants with significantly larger stem diameters compared to BTx623.

Panicle length ranged from 14.5 cm in Mut3515-2 to 48.5 cm in Mut2038#1. Three hundred and forty five M_3 families were significantly different from BTx623, forty two of which were significantly longer. Panicle width was least (2.9 cm) in Mut4213 and widest (8.4 cm) in Mut2616. One hundred and fifty five M_3 families had mean values significantly different from BTx623. Of these, 69 presented mean values significantly longer than BTx623 whilst 87 families had shorter panicles. Twelve families had no peduncle exsertion. These included Mut1204#2, Mut1041#1, Mut1199, Mut1156, Mut0682, Mut0456#1, Mut0672, Mut0056, Mut1113#1, Mut3567, Mut3218 and Mut3220. The longest peduncle exsertion (22.6cm) was observed in family Mut4602#1. One hundred and eighty seven families were significantly different from the control in terms of peduncle exsertion.

Hundred-seed weight ranged from 1.94 g in Mut2899#1 to 4.05 g in Mut3008. Compared to BTx623, significant decreases in seed weight were observed in 44 families whereas higher values were observed in 12 families. The least grain yield (19.4 g) was recorded for Mut3515-2 whilst the highest (203.2 g) was recorded in Mut2157. BTx623 recorded an average grain yield of 67.5 g. Three hundred and thirty mutant families recorded higher grain yields than the control of which 293 were significantly higher ($p < 0.01$).

University of Ghana http://ugspace.ug.edu.gh

Coefficient of variation (CV) ranged from 0.9% for number of leaves to 7.27% for grain yield. Descriptive statistics for the nine quantitative traits are given in Table 4.2 and Figure 4.1. Details of analysis of variance is shown in Table 4.3

Table 4.2. Descriptive statistics of nine evaluated traits

	DTF	PH	NL	SG	PL	PE	PW	HSW	GYP
Minimum	51.10	23.20	7.30	9.69	14.54	0.00	2.85	1.94	19.43
Maximum	70.00	141.90	13.00	28.50	48.45	22.61	10.10	4.05	203.19
Mean of M_3 families	61.53	92.27	10.02	18.48	29.65	6.71	5.77	2.93	73.36
Mean of BTx623	58.60	109.80	12.00	24.50	28.60	3.30	5.70	3.10	67.46
Grand mean	61.86	95.24	10.28	19.39	30.17	6.46	5.98	2.94	79.24
Standard error	0.14	0.61	0.04	0.13	0.16	0.16	0.05	0.01	1.21
Sample variance	13.01	233.90	1.12	10.24	17.14	15.82	1.45	0.11	923.01

DTF= Days to flowering; PH = Plant height; NL= Number of leaves; SG = Stem girth; PL = Panicle length; PE = Peduncle exsertion; PW = panicle width; HSW = Hundred seed weight; GYP; Grain yield per plant.

University of Ghana http://ugspace.ug.edu.gh

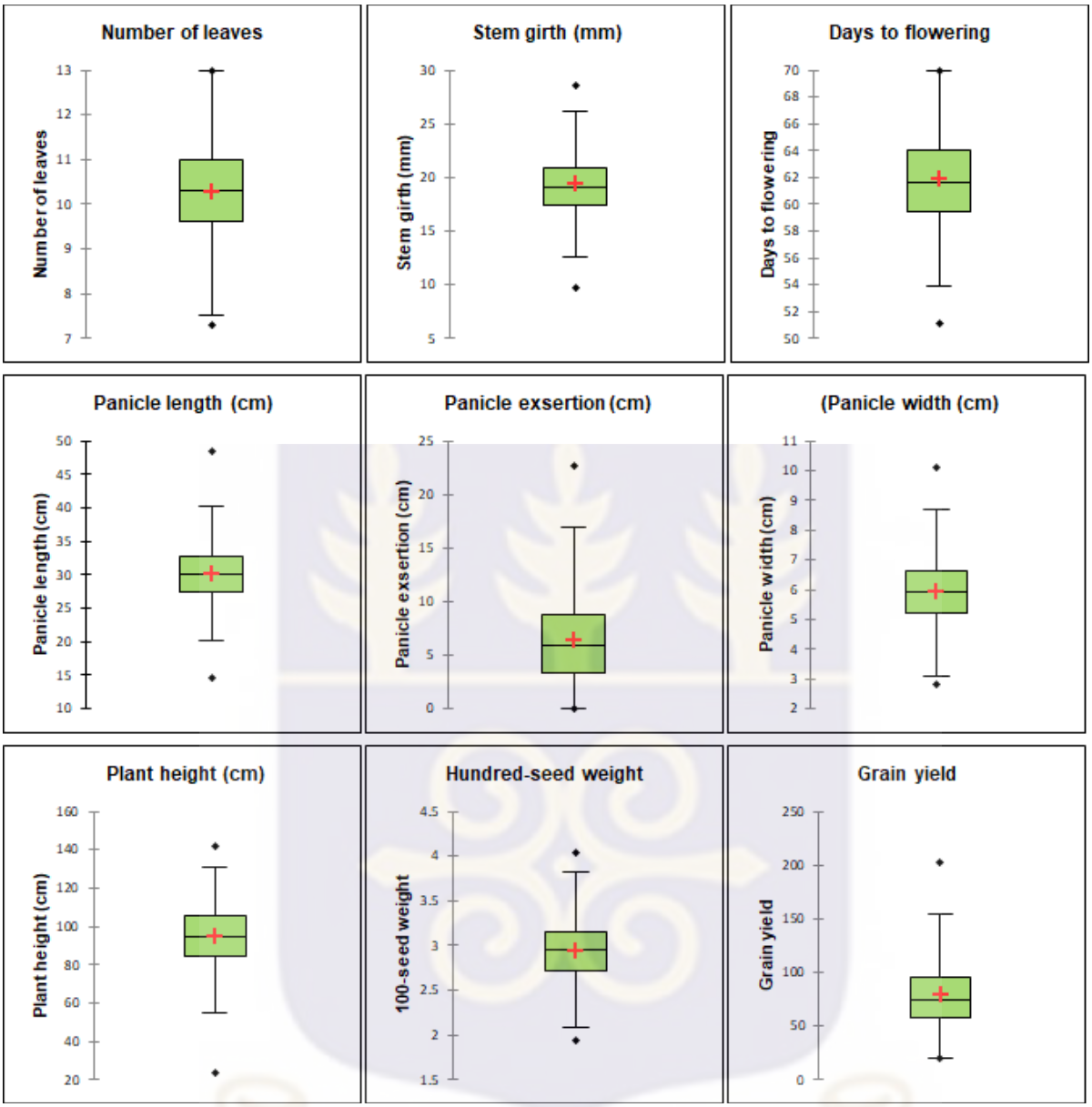


Figure 4.1. Box plots showing the distribution of studied traits in the mutagenised population. The upper, median and lower quartiles represent the 75th, 50th and 25th percentiles of the clusters respectively. The vertical lines represent the variation within the clusters. Dots represent outliers.

University of Ghana http://ugspace.ug.edu.gh

Table 4.3. Analysis of variance within the mutagenised population for quantitative traits

Sources of variation	Df	PL	PE	PW	PH	DTF	NL	SG	HSW	GYP
Genotypes	548	19.34**	18.23**	1.64**	268.97**	14.91**	1.29**	11.48**	0.13**	1059.3**
Blocks	28	6.35**	0.52**	0.28**	8.72**	0.01**	0.01**	32.94**	0.02**	22.8**
Error	84	2.91	0.24	0.17	7.78	0.75	0.01	1.90	0.01	44.70
CV (%)		4.35	8.00	6.99	2.59	1.44	0.92	6.56	4.00	7.27

** Values significant at 0.01 probability levels. PL= Panicle length; PE=Peduncle exsertion; PW= Panicle width; PH= Plant height; DTF= Days to flowering; NL= Number of leaves per plant; SG= Stem girth; HSW= Hundred-seed weight; GYP = Grain yield/plant

University of Ghana http://ugspace.ug.edu.gh

4.3.2. Genetic and phenotypic variances and heritability within the mutagenised population

The lowest GCV values were observed for days to flowering (2.99%) and plant height (3.97%). Peduncle exsertion and grain yield per plant had the highest GCV values of 31.31 and 19.63% respectively. PCV values were slightly higher than GCV values for all traits. Peduncle exsertion, hundred seed weight and panicle width showed the highest PCV values 33.15, 22.76 and 19.31% respectively. Heritability estimates varied from 0.60 for stem girth to 0.90 for number of leaves. Estimates for broad sense heritability, genetic and phenotypic coefficients of variation are presented in Table 4.4.

Table 4.4 Summary of estimated variances and heritability for quantitative traits

Traits	σ^2g	σ^2p	GCV%	PCV%	H^2
Panicle length	3.62	5.32	6.31	7.64	0.68
Peduncle exsertion	4.10	4.59	31.31	33.15	0.89
Panicle width	0.92	1.33	16.07	19.31	0.69
Plant height	13.61	16.42	3.97	4.25	0.83
Days to flowering	3.42	4.29	2.99	3.35	0.80
Number of leaves	0.87	0.96	9.08	9.55	0.90
Stem girth	2.00	3.35	7.29	9.44	0.60
Hundred seed weight	0.33	0.45	19.63	22.76	0.74
Grain yield per plant	24.34	31.05	6.23	7.03	0.78

σ^2g = genetic variance; σ^2p = phenotypic variance; GCV = Genotypic coefficient of variation, PCV = Phenotypic coefficient of variation; H^2 = broad sense heritability.

University of Ghana http://ugspace.ug.edu.gh

4.3.3 Correlation between the studied traits

Significant ($p<0.05$) associations were observed between several traits with majority (15 pairs) exhibiting correlations greater than 0.3. These included grain yield/number of leaves (*r=0.447*) and grain yield/hundred seed weight (*r=0.482*). Both grain yield and panicle width were also significantly ($p < 0.05$) and positively correlated with panicle length and stem girth. The highest correlation coefficient (*r=0.716*) was between grain yield / panicle width. Peduncle exsertion was negatively correlated with all traits except plant height and days to flowering. A few of the correlations between the traits were low and not significantly different ($p<0.05$). This was mostly observed between DTF and other traits. For example, DTF/PH (*r=0.019*), DTF/NL (*r=-0.062*) and DTF/GYP (*r=0.053*). The phenotypic correlation among all pairs of traits is shown in Table 4.5.

University of Ghana http://ugspace.ug.edu.gh

Table 4.5. Pearson's correlation coefficients of quantitative traits among 550 genotypes

Traits	PL	PE	PW	PH	DTF	NL	SG	HSW	GYP
PL	**1**								
PE	**-0.222**	**1**							
PW	**0.610**	**-0.318**	**1**						
PH	**0.453**	0.058	**0.349**	**1**					
DTF	0.003	0.019	**-0.110**	-0.044	**1**				
NL	**0.279**	**-0.259**	**0.378**	**0.313**	-0.026	**1**			
SG	**0.368**	**-0.393**	**0.393**	**0.123**	**0.106**	**0.509**	**1**		
HSW	**0.183**	-0.051	**0.213**	**0.212**	-0.062	**0.166**	**0.156**	**1**	
GYP	**0.644**	**-0.285**	**0.716**	**0.409**	0.053	**0.447**	**0.482**	**0.249**	**1**

Values in bold are different at 0.05 significance level

PL= Panicle length; PE=Peduncle exsertion; PW= Panicle width; PH= plant height; DTF= Days to flowering; NL= number of leaves per plant); SG= Stem girth; HSW= Hundred-seed weight; GYP= Grain yield/plant. P-values can be found in Appendix 2.

University of Ghana http://ugspace.ug.edu.gh

4.3.4 Grouping of genotypes based on principal component analysis

The first three principal components (PC1 to PC3) with eigenvalues greater than 1 were extracted. These accounted for 63.8% of the total variability observed among the 550 sorghum genotypes (Table 4.6). The first principal component (PC1) accounted for 38.4% of the total variance. Grain yield per plant (0.463), panicle width (0.436) and panicle length (0.411) were the most important traits contributing to PC1. On PC1, the highest negative loading was peduncle exsertion (-0.238). The second principal component (PC2) accounted for 13.9% of variability. It showed a strong positive loading with peduncle exsertion (0.556) and plant height (0.527). On the other hand, PC2 showed negative loading with days to flowering (-0.306). The third principal component (PC3) accounted for 11.5% of the total variation with a very high factor loading for days to flowering (0.888).

The loading plot shows that peduncle exsertion, plant height, panicle weight, grain yield and stem girth contributed the highest towards total genetic variation. The first axis differentiated genotypes that had larger panicles, higher grain yield and larger stem girth. The second axis however differentiated genotypes with well-exserted panicles. Results of the principal component analysis showing eigenvalues, percentage variance and cumulative percentage variance are given in Table 4.6. The contribution of the variables to the three principal components are shown in Table 4.7. Loading plots of the traits in the first two factors is shown Figure 4.3. The biplot of the 550 genotypes based on the first two principal components is presented in Figure 4.2.

University of Ghana http://ugspace.ug.edu.gh

Table 4.6. Eigenvalues of first three principal components

Traits	PC1	PC2	PC3
Panicle length	**0.411**	0.178	0.127
Panicle exsertion	-0.238	**0.556**	**0.330**
Panicle width	**0.436**	0.076	-0.112
Plant height	0.288	**0.527**	**0.208**
Days to flowering	-0.009	-0.306	**0.888**
Number of leaves	0.347	-0.155	-0.053
Stem girth	0.358	**-0.417**	0.036
Hundred seed weight	0.192	0.286	-0.119
Grain yield per plant	**0.463**	0.043	0.112
Eigenvalue	***3.459***	***1.248***	***1.032***
Variability (%)	***38.429***	***13.871***	***11.466***
Cumulative %	***38.429***	***52.300***	***63.765***

The highest loadings are shown in bold

Table 4.7. Percentage contribution (%) of the traits PC1, PC2 and PC3

Traits	PC1	PC2	PC3
Panicle length	16.93	3.16	1.62
Panicle exsertion	5.69	**30.90**	10.88
Panicle width	19.05	0.57	1.26
Plant height	8.30	27.80	4.34
Days to flowering	0.01	9.35	**78.82**
Number of leaves	12.05	2.40	0.28
Stem girth	12.85	17.43	0.13
Hundred seed weight	3.68	8.20	1.42
Grain yield per plant	**21.46**	0.19	1.25

The highest percentages are shown in bold

University of Ghana http://ugspace.ug.edu.gh

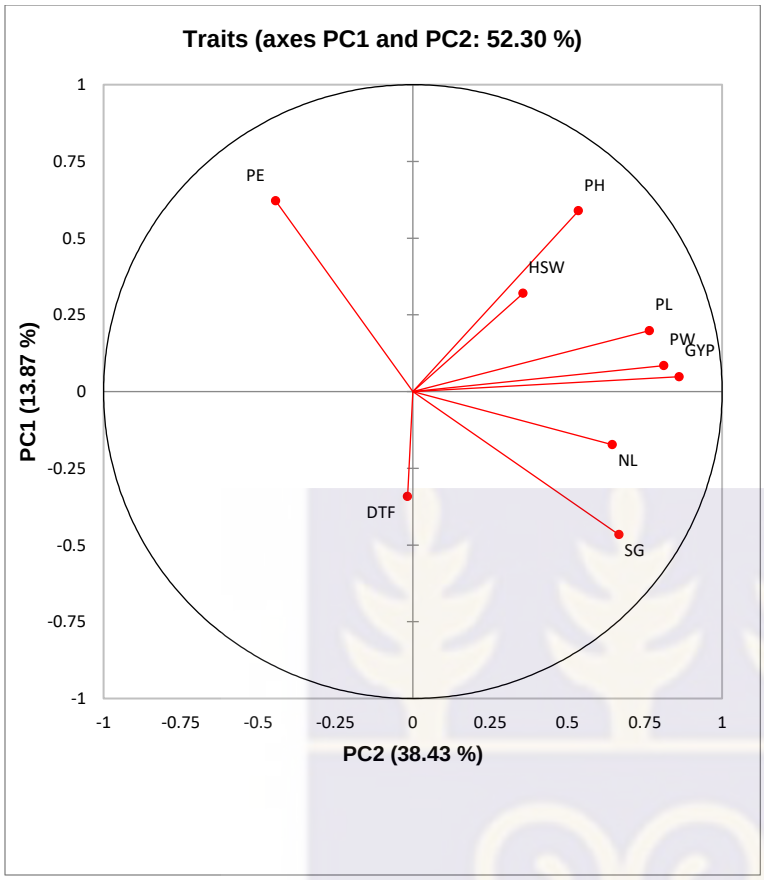


Figure 4.2. Loading plot of PC1 and PC2 showing contribution of quantitative traits to variability

University of Ghana http://ugspace.ug.edu.gh

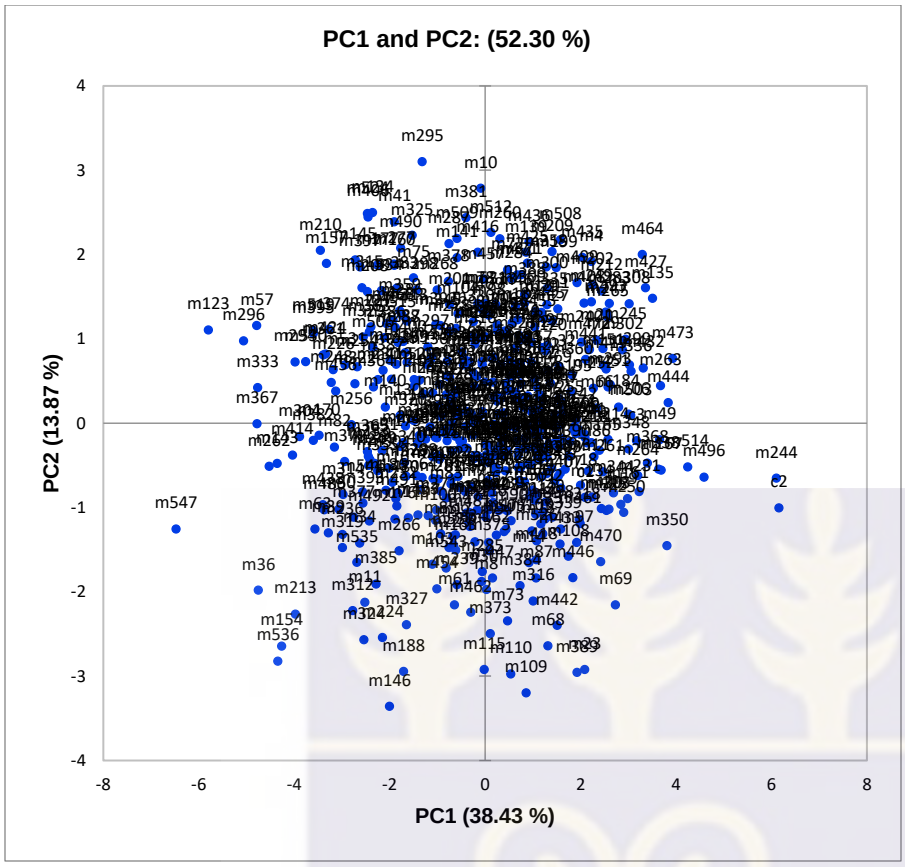


Figure 4.3. Distribution of sorghum genotypes for first two principal components

4.3.5 Divergence between the genotypes based on cluster analysis

The 550 genotypes were resolved into three divergent clusters at 0.52 level of dissimilarity. Cluster I consisted of the largest number of genotypes (297) including the wild-type (BTx623) and the Tx631. Cluster II comprised 133 members whereas Cluster III comprised 120 genotypes including Grinkan. The highest inter-cluster distance (3.07) was observed between Clusters II and III whereas for intra-cluster distances, the highest (3.82) was observed between Clusters I and II. Means of the three clusters for the nine traits are presented in Figure 4.4. The highest grain yield (83.0 g/plant was observed for Cluster I whereas the lowest number of days to flowering (63) was

University of Ghana http://ugspace.ug.edu.gh

observed in Cluster II. The distribution of the genotypes in the different clusters is shown in Appendix 3.

University of Ghana http://ugspace.ug.edu.gh

-

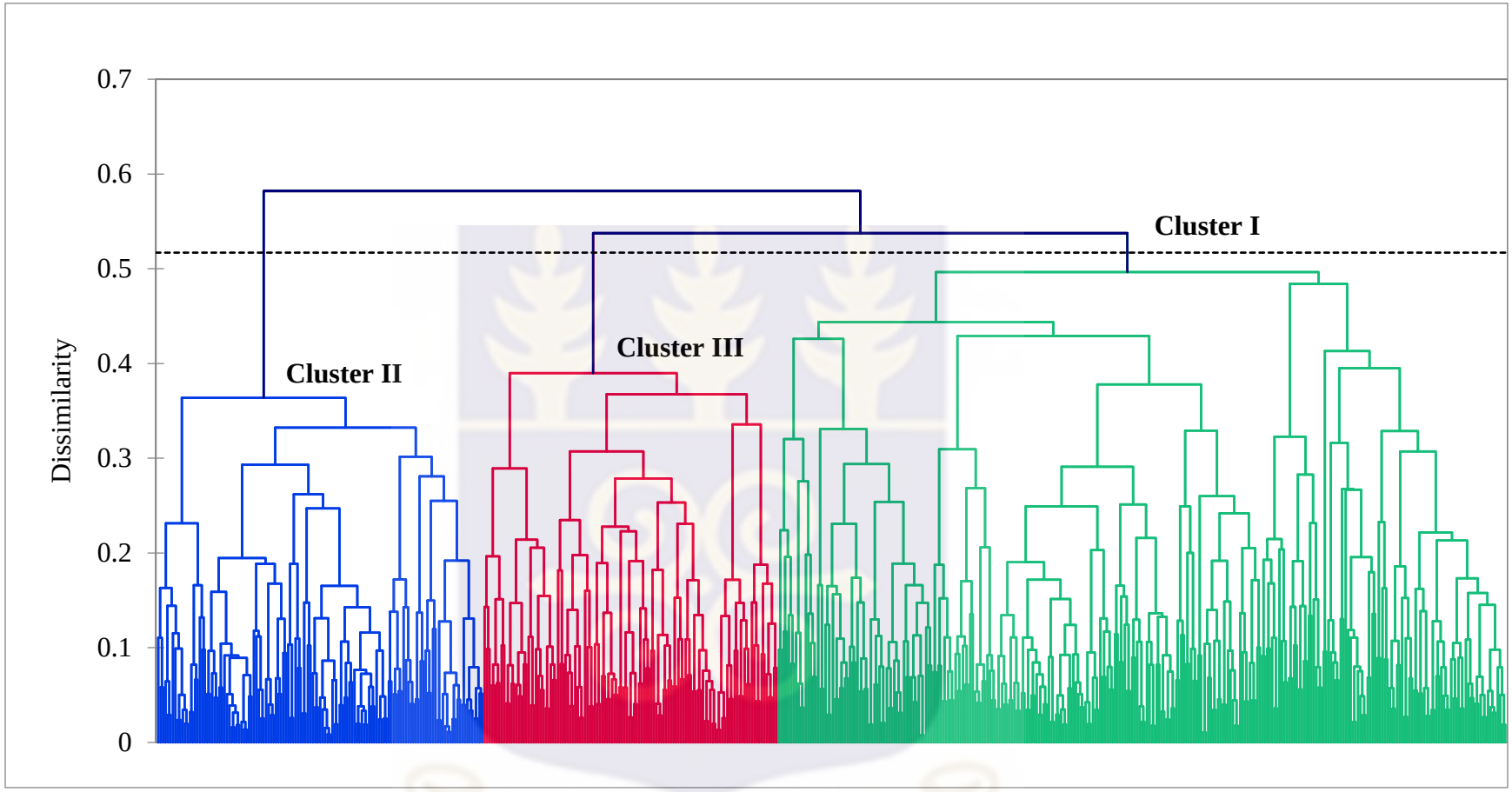


Figure 4.4. Dendrogram of 550 sorghum genotypes derived by UPGMA method (Pearson's dissimilarity matrix) based on standardized data of all morpho-agronomic traits. Cluster I (Green); Cluster II (Blue); Cluster III (Red). Details of the members in each cluster can be found in Appendix 3.

University of Ghana http://ugspace.ug.edu.gh

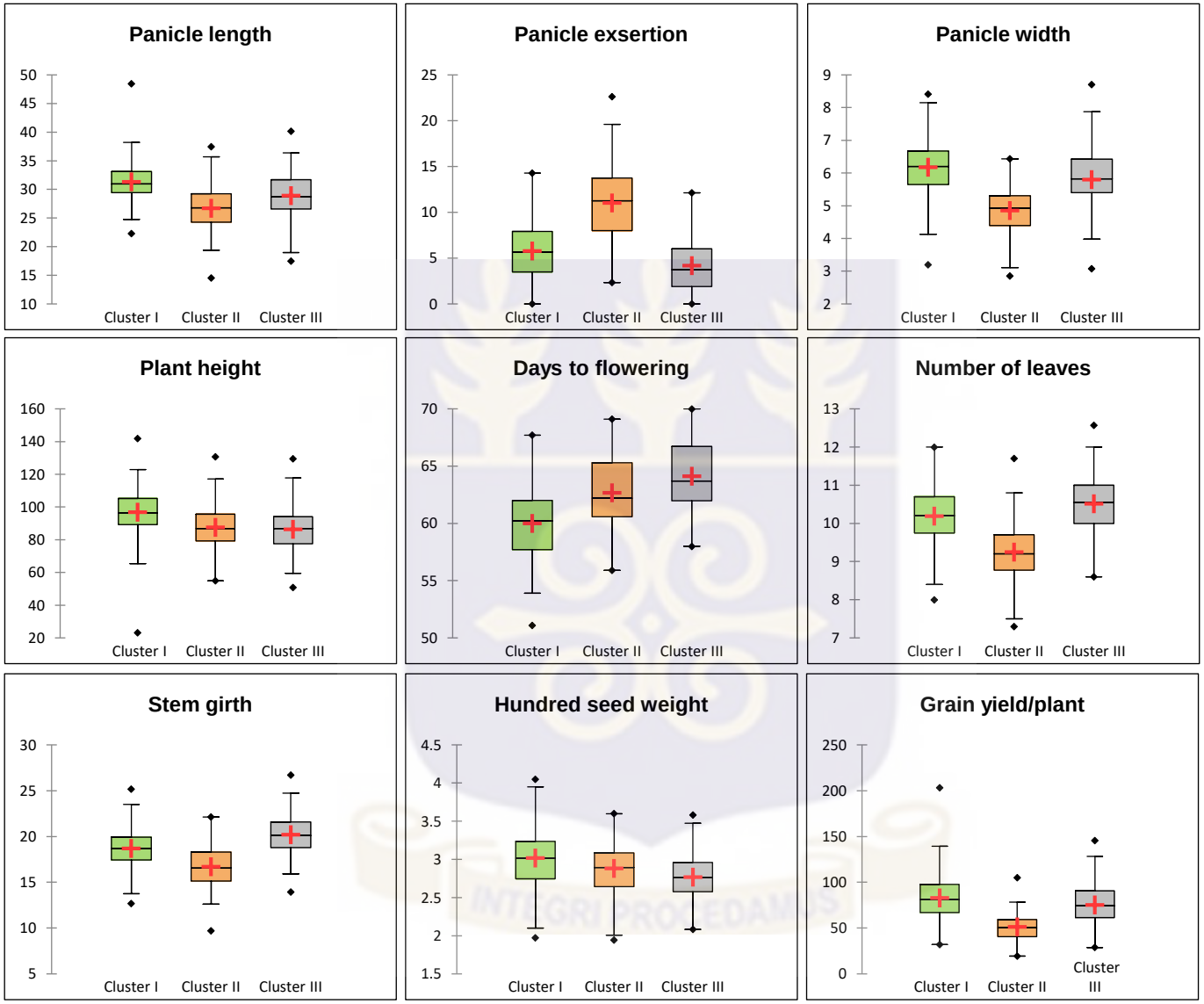


Figure 4.5. Boxplots showing the distribution of traits in each cluster. The upper, median and lower quartiles represent the 75th, 50th and 25th percentiles of the clusters respectively. The vertical lines represent the variation within the clusters. Dots represent outliers.

University of Ghana http://ugspace.ug.edu.gh

4.3.6 Variation within the mutagenised population for qualitative traits

Several distinct traits were observed in the M_3 families with each family exhibiting variation for at least one distinctive phenotype. Segregation for more than one distinct phenotype was observed in 11 mutant families. For example, mutations in both leaf colour and plant height (dwarfing) was displayed in Mut0889. The most frequently-observed mutant phenotypes were leaf-related, most of which were obvious by the flowering stage. Albinism was observed in 16 families. Twenty families segregated for leaf abnormalities such as lesions or spots of various sizes ranging from tiny spots to large necrotic areas. Alterations in leaf pigmentation was also very evident within the population. These included green, yellow and bronze hues. For example, vertical green stripes were observed on leaves of families Mut1865 #1 and Mut0460, yellow leaves in Mut2858 and pale green leaves in families 2899, 1865, 0755, 1043, 1202 and 1302. Leaves with red/purple margins were observed in *Mut3092*. Leaf striations (narrow white vertical stripes) were observed in Mut2904 while zebra cross-bands were observed in Mut1027#2. Survival of these chlorophyll mutants ranged from slight delay in vigour and growth to complete lethality in albinos (white seedlings).

Several variations were also observed in midrib colour (white, dull green or brown). The putative brown midrib (*bmr*) mutant phenotype was easily distinguishable in the field by the distinct brownish-coloured midrib of leaves. This trait was observed in five mutant families (Mut5095, Mut5181, Mut5199 #1, Mut5398 and Mut0008).

In addition to leaf abnormalities and pigmentation mutations, several lines also showed alterations in leaf arrangement. Some plots segregated for multiple plants with erect leaf architecture. This was most distinct in two independent mutant families, Mut0393 and Mut0992 which appeared to segregate for the erect leaf (*erl*) phenotype. These families showed more upright leaves (reduced

University of Ghana http://ugspace.ug.edu.gh

or acute leaf angle between the main shoot and the line from the leaf base to the leaf tip) as described by Xin *et al*., (2015).

Other mutant phenotypes included altered agronomic traits such as number of tillers and early senescence. Tillering ranged from light to profuse across the population. A few mutants showed a tendency for earlier senescence or wilting compared to the wildtype. This was observed in lines Mut0222 #1, Mut0572, Mut2952 and Mut1195.

Segregation in plant size was also observed among the mutant families. In comparison to the wild-type BTx623, mutant families were either tall, semi-dwarf (normal), dwarf or tiny. Plants scored as dwarf were those that presented reduced height but largely normal leaf size and stem thickness. Tiny plants were those that presented a reduction in size of all organs, such as small leaves and thin stems. Mutant family Mut3092 for instance presented extremely short plants with no distinct internodes (rosette). The tallest plants (more than 140 cm) were observed line Mut0120 which maintained erectness in spite of height. Multiple tillering, some of which were upper nodal, was displayed in mutant families 3042, 2927, 2518, 2570, 2571 2573, 2574 and 2575. The bloomless trait (reduction of epicuticular wax) described as well-defined shiny green stems was observed in the line Mut3663.

Variations in seed colour were limited in the population as most lines maintained the white-seeded characteristic of BTx623. Also, most mutants presented normal, fully-developed panicles that were comparable to the wildtype in both shape and size. One mutant family Mut0589, appeared to have the multi-seeded (*msd*) mutant trait as indicated by the relatively large and bulky heads. On the other hand, some lines displayed some abnormalities in panicle development. This ranged from highly-underdeveloped panicles to compact ones that bore no pollen. All distinct and altered phenotypes that were observed within the mutant population are listed in Table 4.8. To illustrate

University of Ghana http://ugspace.ug.edu.gh

the diversity in qualitative traits observed in this mutant sorghum population, a gallery of selected mutant phenotypes is presented in Figures 4.7a to 4.7f.

University of Ghana http://ugspace.ug.edu.gh

Table 4.8. Mutant phenotypes segregating in M_3 families

Category	Mutant name	Abbreviation	Phenotype description
Leaf abnormalities	Crinkly leaf 1	*crl1*	Leaves have a crinkled appearance-raise and lowered bumps
	Leaf rolling 1	*rl1*	Tips of leaves roll, otherwise plant is normal
	Leaf rolling 2	*rl2*	entire leaves roll
Leaf colour	Brown midrib	*bmr1*	leaves have a brown midrib
	Albino plant 1	*wht1*	new seedlings are white or albino
	Chlorotic leaf	*chl1*	leaves have an interveinal chlorotic appearance
	Green stripe	*gst1*	leaves have vertical green stripes
	Light green leaf	*lgl1*	leaves are lighter green than normal
	Red margins	*rmg1*	leaf margins are red
	Virescent seedling 1	*vrs1*	seedling is light green
	Leaf striations 1	*str1*	leaves have many narrow, yellow vertical stripes
	Leaf striations 2	*str2*	leaves have many narrow, white vertical stripes
	Variegated leaf 1	*var1*	leaves have variable widths of white vertical stripes
	Yellow leaf 1	*ylf1*	leaves are yellow
	Yellow leaf splotch 1	*ysp1*	leaves have yellow patches
	Yellow-Green leaf 1	*ygl1*	leaves are light green, yellowing at the tips
	Yellow-Green leaf 2	*ygl2*	leaves are yellow-green, poor growth
	Zebra Cross-bands	*zb1*	leaves mostly yellow-green, with green cross-bands
	Zebra Cross-bands	*zb2*	leaves are green, with yellow-green cross-bands
	White margins 1	*wmg1*	leaf margins and tips are white
Leaf size and shape	Erect leaf 1	*erl1*	leaves erect with very narrow leaf angle
	Grass leaf 1	*grl1*	leaves very narrow with –grass-like appearance
	Grass leaf 2	*grl2*	leaves very narrow with grass-like appearance with many tillers
	Narrow leaf 1	*nrl1*	leaves narrow, normal otherwise
	Wide leaf 1	*wdl1*	leaves are wider than normal
	Pineapple leaf 2	*pnl2*	leaves stacked (short internodes), normal otherwise
	Stacked leaf 1	*stl1*	leaves stacked- short internodes

***Phenotypes were named according to Xin *et al.*, (2008) and USDA Mutant description for sorghum**

University of Ghana http://ugspace.ug.edu.gh

Table 4.8 (Continued). Mutant phenotypes segregating in M_3 families

Category	Mutant name	Abbreviation	Phenotype description
Lesions and necrotic areas	Brown lesions 1	*blsn1*	leaves have brown spots and splotches in some area
	Brown lesions 2	*blsn2*	leaves have vertical brown lesions
	Leaf bronzing 1	*lbr1*	some leaves turn bronze colour
	Leaf bronzing 2	*lbr 2*	all leaves turn bronze colour, sometimes plant dies
	Spot leaf lesion 1	*sp1*	leaves have tiny whitish spots
Plant size	Dwarf plant 1	*dw1*	dwarf with stunted growth
	Rosette plant 1	*rst1*	plant stays close to the ground and resembles a rosette-type plant
	Short plant 1	*sht1*	plants shorter than normal
	Tiny plant 1	*tny1*	plants are very small with narrow leaves
	Tiny plant 2	*tny2*	plants are very small with stunted growth
Tillering	Single-stalked 1	*Tx1*	plants have single-stem, no tillers
	Multiple tillers 1	*mtl1*	plants have multiple tillers, normal otherwise
	Multiple tillers 2	*mtl2*	plants have multiple tillers, shorter than normal
	Multiple tillers 3	*mtl3*	plants have multiple tillers that sprawl out
	Nodal tillers 1	*ntl1*	plants have upper nodal tillers
Senescence and wilting	Early senescence 1	*esn1*	leaves die earlier than normal
	Wilt 1	*wlt1*	leaves wilt and turn yellow
Panicle abnormalities	Underdeveloped panicle 1	*udp1*	head not well-formed
	Underdeveloped panicle 2	*udp2*	head looks compact
	Underdeveloped panicle 3	*udp3*	head formed but never produces pollen
Other	Bloomless 1	*blm1*	stems do not have epicuticular wax
	Bloom	*blm*	stems have epicuticular wax

*Phenotypes were named according to Xin *et al*., (2008) and USDA Mutant description for sorghum

University of Ghana http://ugspace.ug.edu.gh

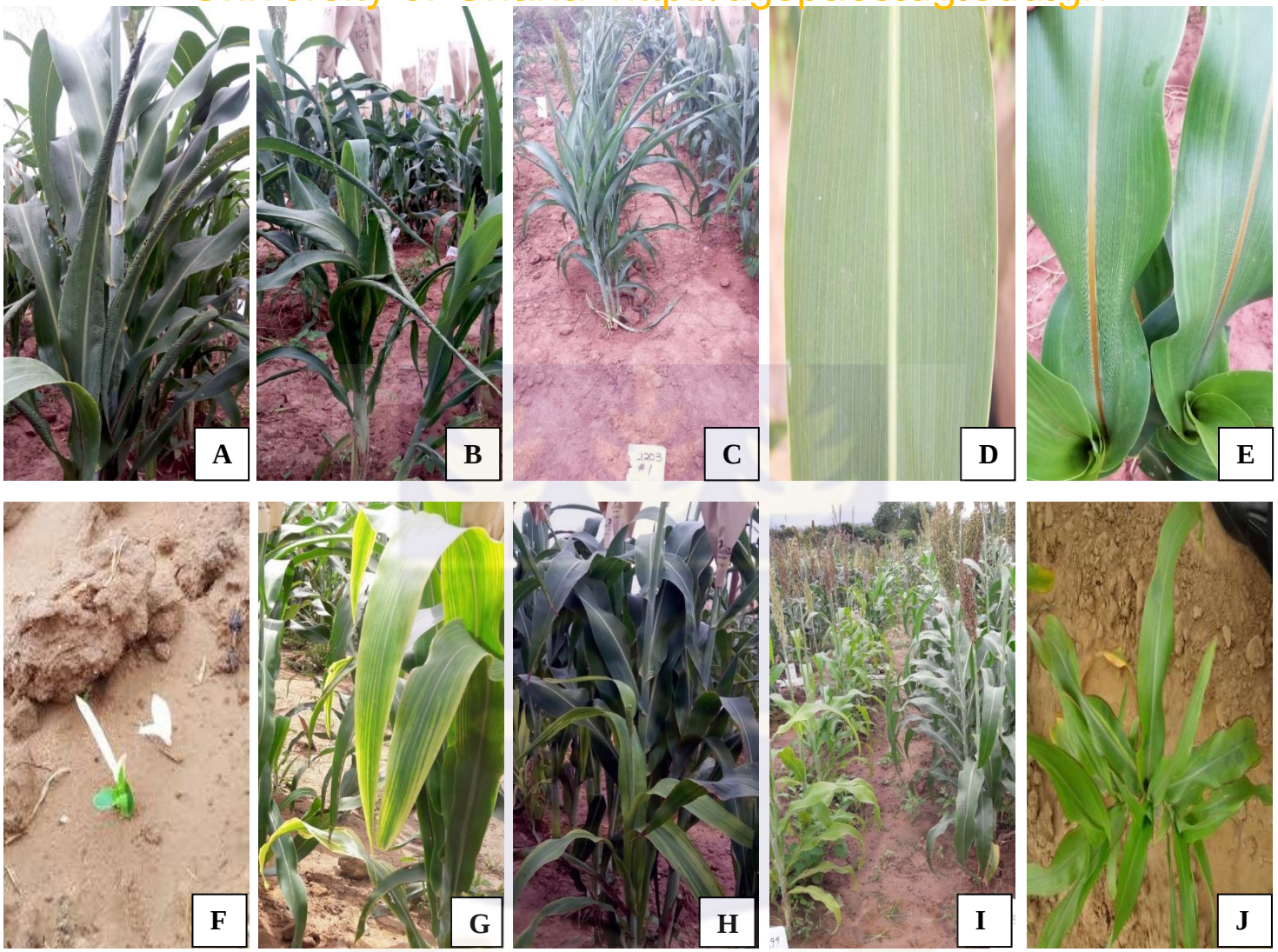


Figure 4.6a: Variations in leaf midrib and blade colour (A): crinkly leaf (crl1); (B): leaf rolling 1 (rl1); (C): leaf rolling 2 (rl2) Leaf colour: (D): cream midrib (wildtype); (E): brown midrib (bmr1); (F): albino plant (wht1); (G): chlorotic leaf (chl1); (H): green stripe (gst1); (I): light green leaf (lgl1) (J): Red margins (rmg1)

University of Ghana http://ugspace.ug.edu.gh

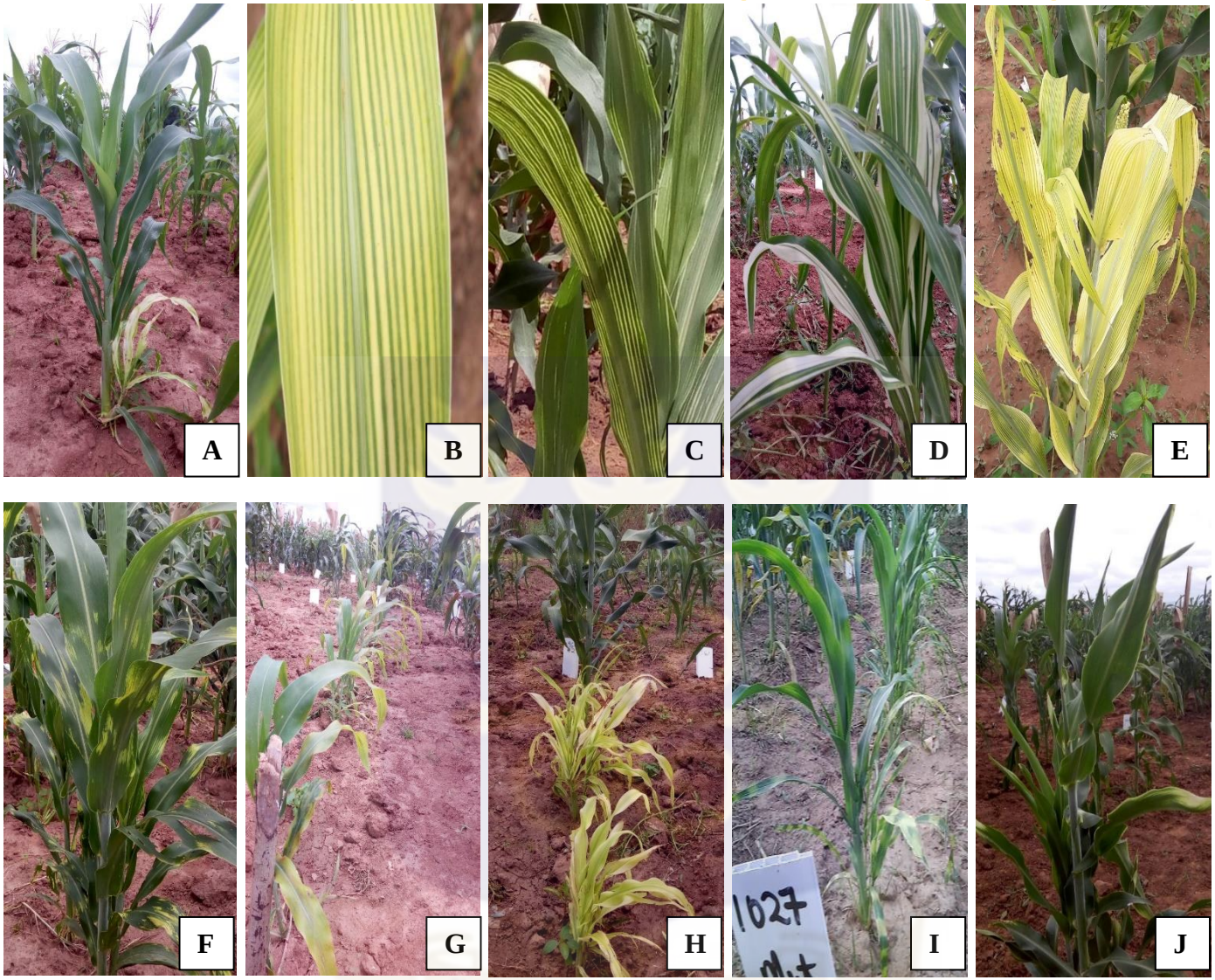


Figure 4.6b: Variations in leaf colour (A): Virescent seedling 1 (vrs1); (B): Leaf striations 1 (str1); (C): Leaf striations 2 (str2); (D): Variegated leaf 1 (var1); (E): Yellow leaf 1 (ylf1); (F): Yellow leaf splotch 1 (ysp1); (G): Yellow-green leaf 1 (ygl1); (H): Yellow-green leaf 2 (ygl2) Leaf colour: (I): Zebra cross-bands 1 (zb1); (J): White margins 1 (wmg1)

University of Ghana http://ugspace.ug.edu.gh

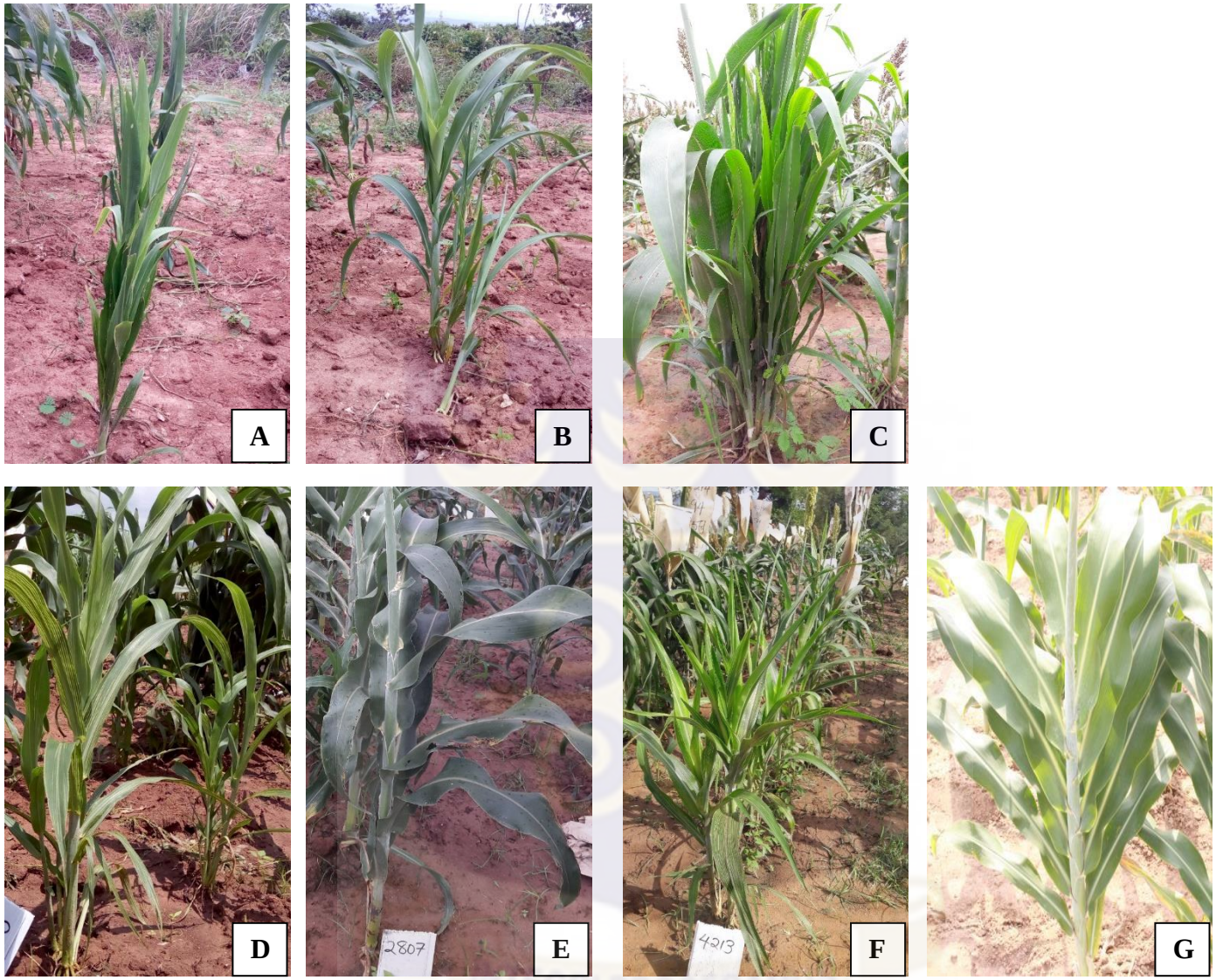


Figure 4.6c: Variations in leaf size (A): Erect leaf 1 (erl1); (B): Grass leaf 1 (grl1); (C): Grass leaf 2 (grl2); (D): Narrow leaf 1 (nrl1); (E): Wide leaf 1 (wdl1); (F): Pineapple leaf 1 (pnl1); (G): Stacked leaf 1 (stl1)

University of Ghana http://ugspace.ug.edu.gh

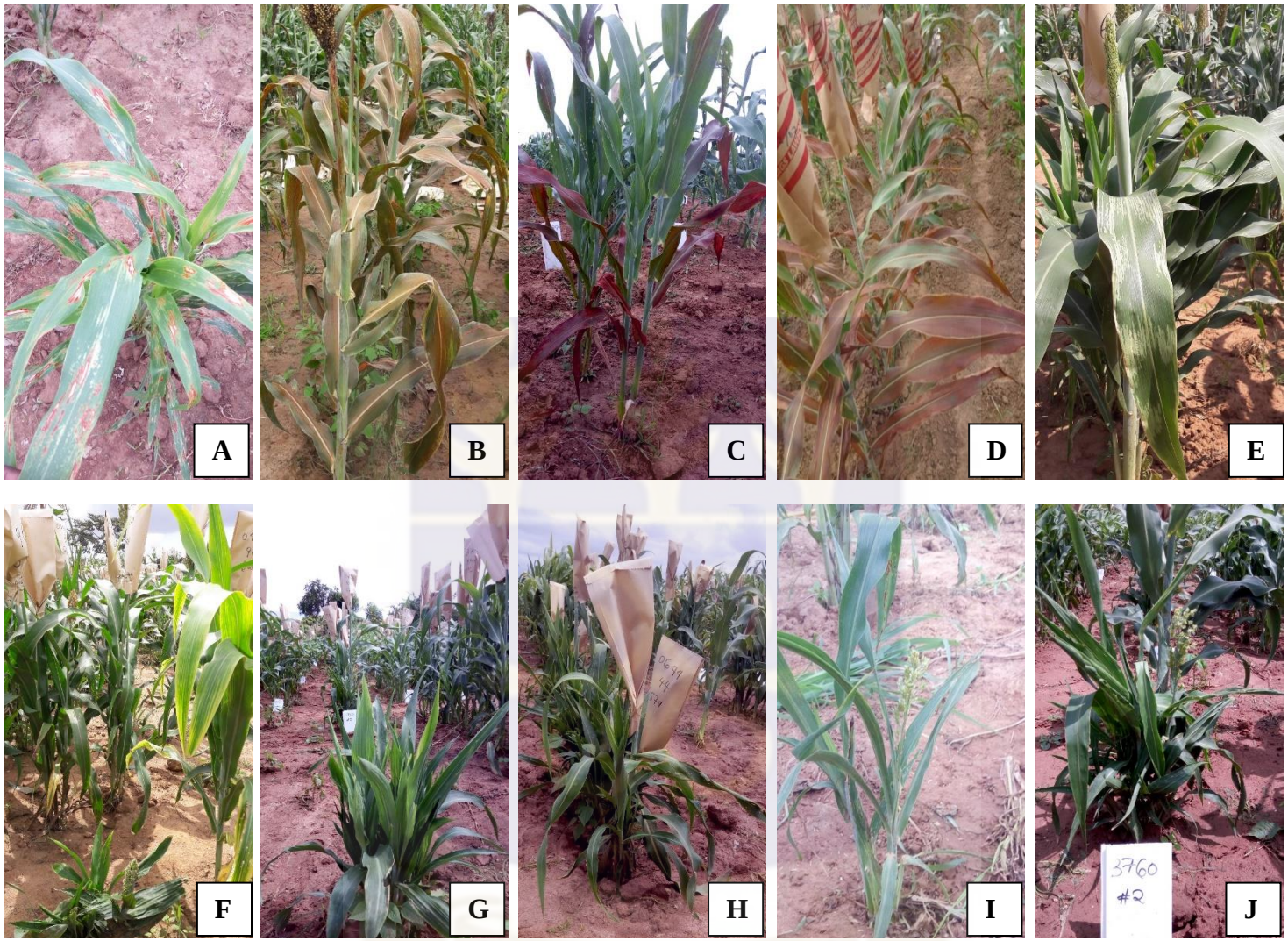


Figure 4.7d: Variations in plant architecture (A): Brown lesions1 (blsn1); (B): Brown lesions (blsn2); (C): Leaf bronzing 1 (lbr1); (D): Leaf bronzing 2 (lbr2); (E): Spot leaf lesion 1 (sp1) Plant size: (F): Dwarf plant 1 (dw1); (G): Rosette plant 1 (rst1): (H): Short plant 1 (sht1); (I): Tiny plant 1 (tny1); (J): Tiny plant (tny2)

University of Ghana http://ugspace.ug.edu.gh

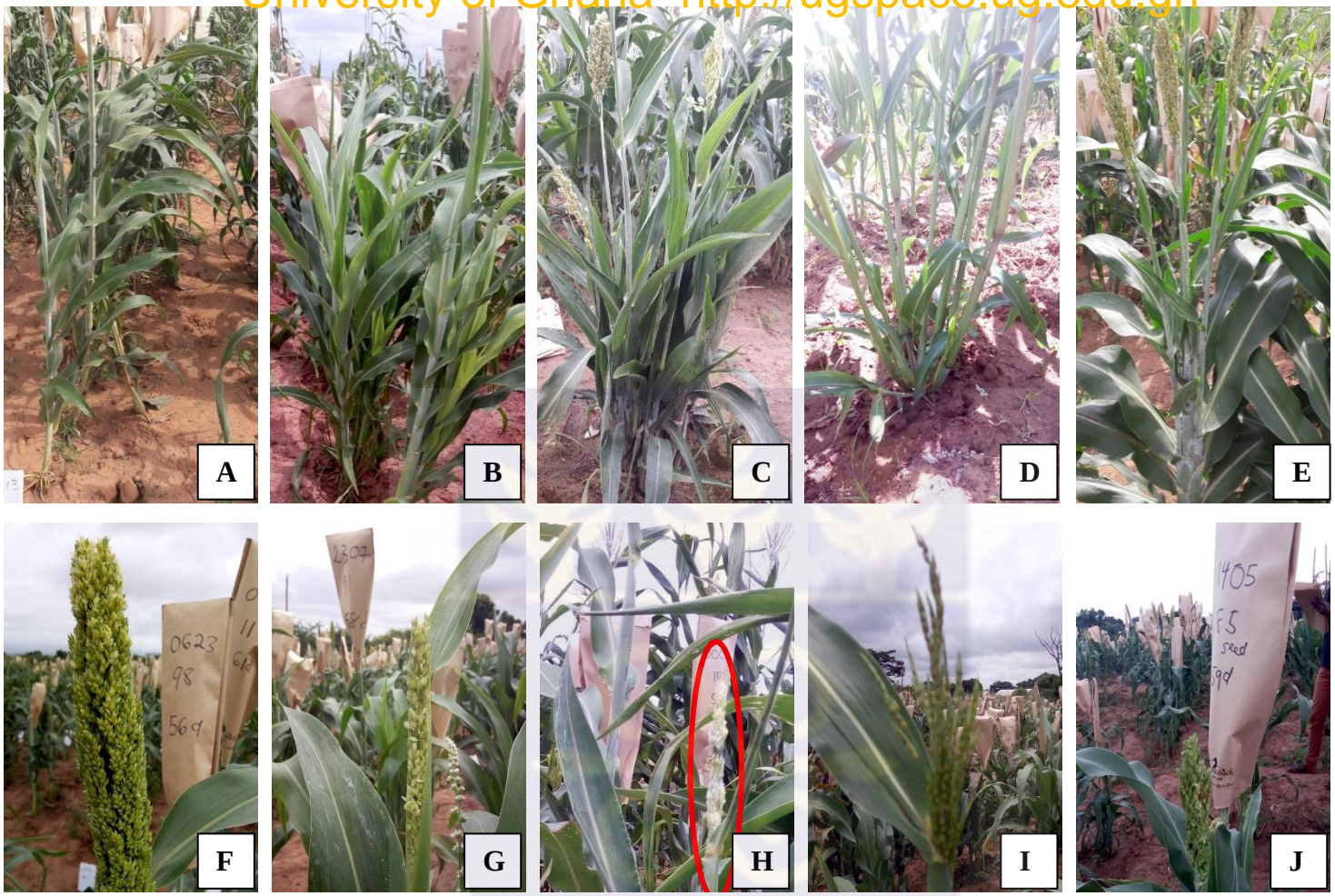


Figure 4.6e: Variations in tillering and panicles (A): Single-stalked 1 (Tx1): (B): Multiple tillers 1 (mtl1): (C): Multiple tillers 2 (mtl2); (D): Multiple tillers (mtl3); (E): Upper nodal tillers (ntl1) Panicle abnormalities: (F): normal panicle (G): underdeveloped panicle 1 (udp1) (H): underdeveloped panicle 2 (udp2); (I): underdeveloped panicle (udp3); (J): undeveloped panicle

University of Ghana http://ugspace.ug.edu.gh

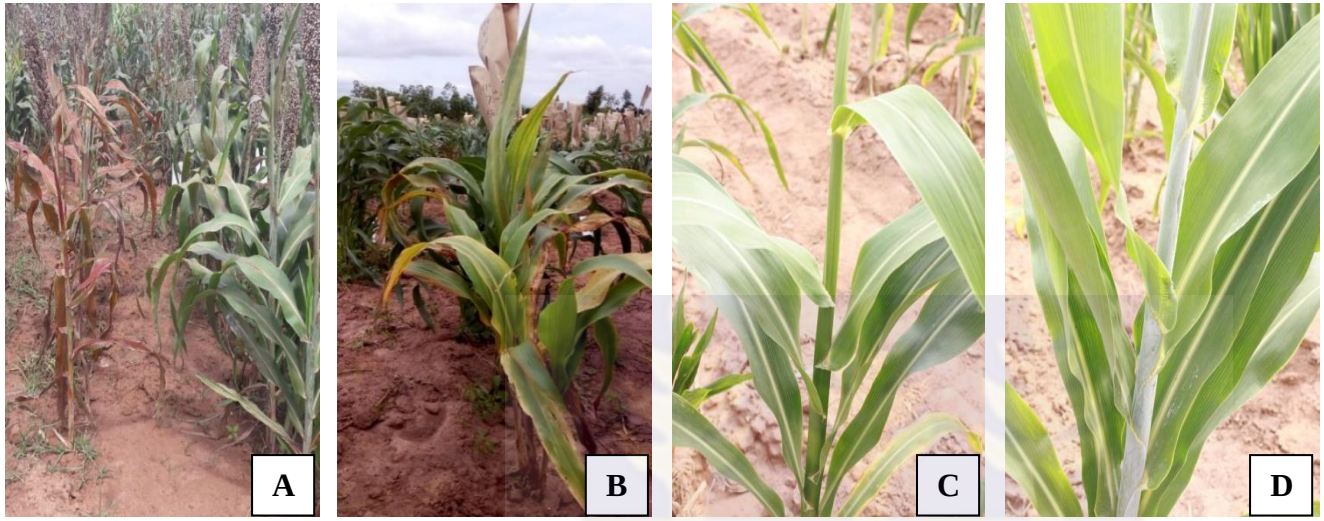


Figure 4.6f: Variations in bloom: Senescence and wilting: (A): early senescence 1 (esn1); (B): Wilt 1 (wlt1); Bloom: (C): Bloomless (blm1); (D): Normal bloom

University of Ghana http://ugspace.ug.edu.gh

4.5 Discussion

In any crop species an expansion of genetic divergence within the species is very useful particularly for traits of limited variability (Jiao *et al*., 2016). Thus, in this study, an attempt was made to enhance genetic variability in sorghum via induced mutagenesis.

Significant differences ($p < 0.01$) were observed among the mutagenised families as well as between the mutagenised families and the wildtype BTx623 for all assessed quantitative traits. For instance, wide variability was observed for grain yield with several putative mutant families producing significantly higher grain yield than Btx623. A similar observation was made by Burow *et al*. (2014) where phenotypic analyses of a mutagenised BTx623 population also revealed putative mutants which exhibited significantly higher grain yield than the original. Such mutants, tagged as multi-seeded (*msd*), typically exhibit large bulky panicles and may be exploited for increased grain yield in sorghum (Burow *et al*., 2014).

Besides grain yield, variations in heading dates were also observed within the mutagenised population. Families which showed significant reductions in number of days to anthesis may be classified as early flowering types. Early flowering mutants have been shown to be beneficial in improving grain production whereas late flowering types have potential in improving biomass yield (Xin *et al*., 2009).

Variations in plant height within mutant populations such as observed in this study have been reported by several authors. For instance, Xin *et al*. (2008) reported reduced plant height among sorghum mutants. According to Yamaguchi *et al*. (2016) such dwarf types show increased resistance to lodging and are advantageous for mechanical harvesting. Variations in panicle characteristics such as length and width are important determinants of grain yield in sorghum (Hart *et al*., 2001). As was the case for other assessed traits, panicle length, width and exsertion varied

University of Ghana http://ugspace.ug.edu.gh

widely within the population. Phenotypic variability for these traits give scope for selection and advancement. This indicates an induction of appreciable levels of variability and suggests an expansion of sorghum genetic resources.

Estimates of genotypic coefficients of variation for the traits confirmed the significant variation revealed by ANOVA. GCV was highest for peduncle exsertion and grain yield which suggests wide differences among the mutant lines for those traits. Thus, selections may be possible for these characters. Based on the low GCV values for days to anthesis and number of leaves, it is likely minimal variability was induced by the mutagenic treatment for these traits. The relatively high heritability values associated with number of leaves suggest that the effect of the environment on the expression of this character is minimal compared to the other measured traits. This implies that selection based on this trait has potential to improve the crop.

Correlation analysis revealed high association between grain yield and panicle traits such as width and length. Based on this, it can be expected that wider and longer panicles may result in higher grain yields, an observation corroborated by Hart *et al*. (2001) and El-Din *et al*. (2012). Grain yield was also positively correlated with stem girth which suggests that thicker stems were influential in increasing grain yield in sorghum. A positive correlation between stem girth and days to flowering indicates that late-flowering types are more likely to have larger stems, an observation also made by Zhao *et al*. (2016). The negative correlation between peduncle exsertion and grain yield is similar to an observation made by Mofokeng *et al*. (2017). In their study of the genetic diversity among South African sorghum genotypes a negative association between peduncle exsertion and grain yield was also observed. Information on associations between these traits may allow breeders to simultaneously select desired traits.

University of Ghana http://ugspace.ug.edu.gh

Cluster analysis helped define the relationship between the mutagenised families and the wildtype. The grouping of 233 M_3 families in clusters independent of that of BTx623 suggests considerable genetic divergence between these M_3 families and BTx623. Selections from the various clusters for further breeding is likely to maintain the divergence exhibited within the mutant population. Genetic variation within the mutagenised population was also assessed using qualitative traits. It has been suggested that the occurrence of morphological alterations or novel phenotypes is more likely in mutant populations (Xin *et al*., 2009). Thus, the genotypes were closely inspected for traits such as plant pigmentation, midrib colour and nodal tillering. A wide variety of distinct phenotypes was observed several of which were similar to those reported by Xin *et al*. (2008) and Jiao *et al*., (2016). The most visual phenotypes were modifications in leaf pigmentation. Virescent, pale green, albino, variegated and yellow leaves were observed in several M_3 families. Tan *et al*. (2008) explains that such alterations in leaf colour may be caused by disruptions in genes essential for chlorophyll synthesis. The chlorophyll mutations attests to the efficiency of EMS in inducing high density mutations in sorghum (Wu *et al*., 2005).

The mutant population also showed alterations for several relevant agronomic traits. For example, the brown midrib (*bmr*) trait was observed in several mutant families. Brown midrib mutants derived through chemical mutagenesis have been reported in sorghum (Saballos *et al*., 2008). The trait, associated with reduced lignin content results in increased conversion efficiency of biomass to ethanol and improved forage digestibility (Sattler *et al*., 2014). The putative *bmr* mutants observed in this study may be useful as forage for livestock or for biofuel production (Yan *et al*., 2012).

Other observed phenotypes include the erect leaf architecture. This feature is distinct from the typical open canopy in wildtype BTx623 in that, leaves are shorter with more acute angle between

University of Ghana http://ugspace.ug.edu.gh

the leaf and the stem (Xin *et al*., 2015). Erect leaf types have been shown to contribute significantly to yield increases through improved distribution of solar radiation to lower leaves which results in greater photosynthetic efficiency (Duvick and Cassman, 1999; Narayan *et al*., 2014). The trait has also been reported to improve drought tolerance and allow higher planting densities on limited land resources (Saballos *et al*., 2008; Sattler *et al*., 2012). Until recently, the trait has not been fully exploited in sorghum due to limited genetic variation (Assefa and Staggenborg, 2011). However, two erect leaf (*erl*) sorghum mutants have been isolated from an EMS-mutagenised BTx623 in a similar study by Xin *et al*., (2015). Putative erect leaf types isolated in this study may be useful in improving yield in sorghum. The mutants may be confirmed by further characteristion through the measurement of leaf angles, length and width of leaves as well as panicle length and exsertion as reported by Xin *et al*. (2015).

A putative bloomless mutant was also observed as indicated by the absence of the white epicuticular wax or the glossy appearance of the stem (Maiti *et al*., 1984). In contrast, wild-type BTx623 typically shows profuse deposition of epicuticular wax on stems and leaves, a feature which plays an important role in drought tolerance as well as tolerance to fungal pathogens such as *Exserohilum turcicum* (Burow *et al*., 2008). However, some reports associate bloomless sorghum with improved resistance to sheath blight (*Rhizoctonia solani* Kuehn) and green bug [*Schizaphis graminum* Rondani] (Jenks *et al*., 1994; Mizonu *et al*., 2013). The putative bloomless mutant identified here might have application in areas where the green bug and sheath blight are important stresses after resistance to these stresses have been confirmed.

Lastly, other putative mutants which have potential application are those which exhibited multiple tillering and early senescence. Multiple tiller mutants were distinguishable from wildtype BTx623 by the presence of four to ten tillers as opposed to a maximum of three stalks in the wildtype (Xin

University of Ghana http://ugspace.ug.edu.gh

et al., 2009). Multiple tillering types may be useful for enhancing biomass yield under intense management whereas early senescing types may be useful for early dehydration of biomass for use as livestock feed (Jiao *et al*., 2016).

4.6 Conclusion

A mutagenised sorghum population was generated using the chemical mutagen EMS. The population was phenotyped in the field for traits such as panicle length, width and exsertion, plant height, grain yield and days to flowering. Significant variation was observed among the putative mutants and between the putative mutants and the wildtype BTx623. Multivariate analysis confirmed the variability within the mutagenised population by the clustering of the M_3 families into three divergent clusters. An assessment of qualitative traits also revealed several phenotypes distinct from the wild-type BTx623. Of these, several desirable mutants were identified which have potential use in plant breeding and/or crop production. These include putative mutants for; early flowering (Mut2619), late flowering (Mut0878), brown midrib (Mut5095, Mut5181, Mut5199#1, Mut5398 and Mut0008), multiple-tillering (Mut3042, Mut2927, Mut2518, Mut2570, Mut2571, Mut2573 and Mut2574), bloomless (Mut3663), erect leaf architecture (Mut0393 and Mut0992) and multi-seeded (Mut0589).The diversity observed within the mutagenised population suggests that it is a useful germplasm resource for both forward and reverse genetic studies.

University of Ghana http://ugspace.ug.edu.gh

CHAPTER FIVE

GENETIC VARIATION FOR PHOSPHORUS-USE EFFICIENCY AMONG MUTAGENISED SORGHUM LINES

5.1 Introduction

In West Africa, available phosphorus (P) levels in cultivated soils can be as low as 2 mg P/kg (Buekert *et al*., 2001). This is a major constraint particularly for traditional crops such as sorghum which are usually cultivated under low-input conditions (Leiser *et al*., 2012). Under such conditions, seed germination, seedling vigor and overall plant growth are adversely affected resulting in significant losses in grain yield (Doumbia *et al*., 1993; Leiser *et al*., 2012). Given its key role as a food staple in many West African rural communities, low sorghum yield coupled with rapid growth in human population threatens to worsen food insecurity in the region (Gemenet *et al*., 2016).

One of the key strategies for mitigating the effects of soil infertility on sorghum is increased fertiliser use among smallholder farmers (Gemenet *et al*., 2016). Unfortunately, fertiliser use in West Africa is severely constrained by farmers' inability to afford the commodity, its frequent unavailability on rural markets as well as farmers' misgivings on achieving maximum net returns on fertiliser use (Kaizzi *et al*., 2012; Rware *et al*., 2014). Even when applied, incorrect timing rates and rates of application are factors that affect efficient fertiliser-use among smallholders (Rware *et al*., 2014). Moreover, increased use of P fertilisers is not sustainable due to depletion of world phosphorus reserves (Gemenet *et al*., 2016). The cost of P fertilisers are expected to increase, thus making the commodity even more inaccessible to smallholder farmers in resource-poor regions (Cordell and White, 2015). In view of these constraints, increased fertiliser-use among smallholders as a strategy to improve sorghum productivity on West Africa's marginal soils, must be complemented with other approaches.

University of Ghana http://ugspace.ug.edu.gh

One such approach is the development of P-use efficient varieties. Until recently, research targeted at improving P-use efficiency in sorghum has been limited in West Africa (Leiser *et al*., 2012). The most significant work is that reported by Leiser *et al*. (2015), in which selection strategies for P-use efficiency were researched in West African germplasm. They report useful genetic variation for P-uptake efficiency in Guinea landraces and utilisation efficiency in Caudatum-derived cultivars. However, both uptake and utilisation efficiency was found to be lacking in any single genotype (Leiser *et al*., 2015). Given the extremely low-P status of West African soils and its negative impact on sorghum yield, the development of varieties which show improved levels of both uptake and utilisation efficiencies is worthwhile. An expansion of the genetic variability for both traits will also be useful in future breeding programmes.

These goals can be approached in several ways. The traditional approach is hybridisation, for instance of the two genetic pools identified by Leiser *et al*. (2015). However, this method usually requires the development of inbred lines, followed by several years of backcrossing. In complement to recombinant breeding, induced mutagenesis offers a rapid and efficient method for generating novel variability for important agronomic traits in crops (Bentley *et al*., 2000). For example, it was applied in the development of sorghum varieties with improved lysine content and early flowering (Sree Ramulu, 1970a; Quinby, 1975; Oria *et al*., 2000). The primary advantage of artificial mutagenesis is that desirable mutants may be released directly as varieties without the need for several years of backcrossing (Ahloowhalia, 2004).

Thus, the goal of this study was to assess the genetic variability for P-uptake and utilisation efficiency among a population of mutagenised sorghum as a step towards identifying new sources of P-use efficiency in sorghum.

The specific objectives were to;

University of Ghana http://ugspace.ug.edu.gh

1. assess the genetic variation for P-use efficiency among mutant and cultivated genotypes under screen-house conditions,
2. confirm any observed diversity for P-use efficiency under field conditions and
3. determine differences between mutant genotypes and cultivated genotypes.

5.2 Materials and methods

5.2.1 Evaluated genotypes

Two hundred sorghum genotypes were evaluated comprising 170 mutagenised families and 30 cultivated genotypes. The mutagenised lines were selected from previous experiments in 2014 and had been advanced from M_3 to M_6 by controlled self-fertilisation. Included in the 30 cultivated genotypes were Grinkan, a P-use efficient genotype (Leiser *et al*., 2012) and Kadaga, a variety frequently grown in northern Ghana. These two genotypes served as control varieties. With the exception of Kadaga, all genotypes were sourced from the Whistler laboratory, Purdue University. A summary of the 31 cultivated lines included in this study and their important features are listed in Table 5.1.

University of Ghana http://ugspace.ug.edu.gh

Table 5.1. Summary of the cultivated genotypes and their important features

Genotypes	Important feature
Kuyuma (WSV387)	Food-grade – Zambia
Sepon82	Food-grade – Niger
Ajabsido	Post-flowering drought tolerance – Sudan
CE-151-262-A1	Food-grade – Senegal
CSM-63	Popular Guinea – Mali
Koro Kollo	Pre-flowering drought tolerance Sudan
Feterita Gishesh	Preflowering drought tolerance – Sudan
Segeolane	Preflowering drought tolerance – Botswana
PI609567 - ErtHdDur D/D N. Mali	Erect-head dhurra - N. Mali
Wassa	Food-grade guinea – Mali
Seguetana	Food-grade guinea – Mali
El Mota - S241	Pre-flowering drought tolerance – Niger
Honey Drip	Sweet sorghum
Theis	Sweet sorghum
Mace Da Kunya (MDK)	Late-season dune sorghum - Niger
MR732	Male-parent – Niger
Tx430	Elite yellow pollinator
BTx2752	Elite red seed parent
TX 436	Elite food-grade male
TX631	Elite food-grade seed parent
Framida	Striga resistant - Burkina Faso
ICSV1049	Striga resistant - Burkina Faso
Sariaso 14	Striga resistant - LGS - Burkina Faso
Grinkan	P-use efficient (Food Grade Guinea – Mali)
TxARG1	High grain yield
BN223	Male-sterile parent
SC599	Stalk rot resistant and post-flowering drought tolerant
Mota Maradi	Improved variety - Niger
Honeydrip	Sweet sorghum
SC35	Charcoal rot resistant
Kadaga East	Popular variety (northern Ghana)

University of Ghana http://ugspace.ug.edu.gh

5.2.2 Description of study sites

Pot experiments were carried out at the Biotechnology and Nuclear Agricultural Research Institute (BNARI) of the Ghana Atomic Energy Commission (Latitude 5º40'N and Longitude 0º 13'W). Field experiments were conducted at the research farm of the University of Ghana, Legon, (Latitude 5º36'N, Longitude 0º10W), approximately 8.8 km from BNARI. A more-detailed description of the research farm is given in the previous chapter. Meteorological data for the experimental areas during the study period is given in Table 5.2.

Table 5.2. Meteorological data for University of Ghana research farm during the study period

		Mean monthly temperature (ºC)	
Year/ month	Total monthly rainfall (mm)	Maximum	Minimum
2015			
May	139.3	32.7	25.0
June	295.1	-	-
July	53.8	29.1	-
August	2.0	29.9	23.1
2016			
July	49.7	29.2	23.6
August	16.9	28.8	23.1
September	-	-	-
October	-	-	-

Source: Ghana meteorological agency (2015, 2016)

5.2.3 Soil sampling and analyses

For the pot experiment, soils were sampled from several sites at Berekusu in the Eastern Region of Ghana. The selected sites had no recent history of crop cultivation and/or fertiliser application. Samples were collected from the plough layer (0 to 20 cm in depth) using the auger after which all debris were removed. The soil samples were then air-dried for seven days, homogenized and

University of Ghana http://ugspace.ug.edu.gh

passed through a 2mm sieve to obtain fine earth. Subsequently, physical and chemical analyses were carried out at the University of Ghana Soil Science Laboratory. Analyses included determination of soil texture (Bouyoucos, 1951) and pH. Organic carbon content was determined using the wet combustion method of Walkley and Black (1934) whereas Total N was determined by the Kjeldahl digestion method. Available-P was extracted by the Bray-1 method and analysed using the molybdate blue procedure (Murphy and Riley, 1962). Cation exchange capacity (CEC) was determined by saturation with 1 N ammonium acetate (NH_4OAc, pH 7.0) and extraction of ammonium with 2M potassium chloride (TSBF, 1993). Cations (Ca, K and Mg) were extracted by the Mehlich- 3 procedure (Mehlich, 1984) and determined by absorption spectrophotometry. Undisturbed soil samples were taken for bulk density determination. All analyses were carried out in triplicate and the results averaged. Details of procedures for soil characterisation and analyses is given in Appendix 4. Soils for all experiments were selected based on available P content.

For low P soils, critical point for available-P was less than 10 mg P/kg (Doumbia *et al*., 1993). The physico-chemical properties of the soils in all the trials are shown in the results. Following soil analyses, top soil was harvested from suitable sites for the pot experiment. Harvested soil was passed through sieves to remove all debris and obtain fine earth. Large polythene bags were used as pots; these were filled with equal quantities (approximately 10 kg) of sieved soils after which the soils were allowed to equilibrate for two weeks before sowing.

5.2.4 Experimental design and layout

The experimental design for the pot experiment was a two-factor (fertiliser level and genotype) factorial arranged in a randomized complete block design. Each genotype was allocated twelve pots in total. Thus, the total number of experimental pots was 2,400. The pots were grouped into

University of Ghana http://ugspace.ug.edu.gh

four blocks; two blocks per P treatment. In each block, each genotype was represented by three pots making a total of 6 pots per P environment. Two P treatments were imposed at sowing; 0 mg P/kg (control) and 50 mg P/kg P_2O_5 (from triple super phosphate – TSP). Three seeds were sown per pot. Fourteen days after planting seedlings were thinned to two per pot. All pots received nitrogen from urea (46-0-0) at 80 mg N /kg and potassium from muriate of potash at 40 mg K / kg of soil. Standard agronomic and plant protection practices were followed during the cropping season.

Field trials were conducted in the 2016 cropping season. The experiment consisted of two separate and contrasting P fields; one with P fertilisation and one without. In each trial, the 200 genotypes were sown in an incomplete block/augmented design. The number of incomplete blocks in each trial was 20. Each block comprised 12 row plots (10 test genotypes plus the two check varieties). The plots measured approximately three metres with 0.8 m between the plots. Ten hills were planted per row at three seeds per hill. Hills were later thinned to two plants. At sowing, the optimum P field was treated with 40 kg ha $^{-1}$ of triple super-phosphate (TSP). Urea and potash were applied at 50 kg ha $^{-1}$ 40 kg ha $^{-1}$ respectively. To obtain similar units of nitrogen and potassium in both fields, the low P field was treated with urea and potash at 60 kg ha $^{-1}$ and 40 kg/ha respectively. Trials were mainly rain-fed. However, irrigation was provided when necessary. Standard agronomic practices of weed and insect control were used. Soil analyses were repeated six weeks after planting.

5.2.5 Data collection

Data were collected on eight traits. For pot experiments, data were collected on all twelve plants that represented each genotype. With the exception of grain and stover yield, field data were

University of Ghana http://ugspace.ug.edu.gh

collected on five tagged plants in the middle of each plot. A summary of the data collected in the study is given in Table 5.3.

Table 5.3 Descriptions of evaluated traits

Traits	Descriptions
Seedling vigour	Visual score based on a 1 to 5 scale, 1=least vigorous and 5 = most vigorous. This was recorded 28 days after planting.
Days to anthesis	Number of days from sowing to when each tagged plant had flowered.
Plant height	Distance from the base of the plant to the flag leaf at anthesis.
Stem girth	Width of the base of the stem at anthesis.
Stover yield	Average of weight of stover of all plants in a plot
Grain yield	Average of weight of seeds harvested from whole plot.
P concentration in leaves	Leaves were sampled from 3 tagged plants at anthesis and measured as the amount of P (mg) in 1 g shoot dry matter.
P concentration in grain	Grain sampled from 3 tagged plants at physiological maturity and measured as the amount of P (mg) in 1 g dry grain matter.

University of Ghana http://ugspace.ug.edu.gh

Seedling vigour scores were a relative evaluation based on the range of variation for seedling size (height, length and width of leaves) in the genotype under study (Cisse and Ejeta, 2003). Harvested panicles and stover were air-dried at ambient temperature for 10 days prior to weighing. For pot experiments, stover and grain yield were analysed in grams/plant whereas for field experiments the parameters were measured in kg, then converted into tonnes per hectare. Digestion and determination of P concentration in the plant samples were done using the Bhargava and Raghupathi (1984) and Murphy and Riley (1962) protocols respectively (Described in more detail in Appendix 5).

5.2.6 Data analysis

5.2.6.1 Data analysis for pot experiments

Analysis of variance (ANOVA) was performed on all traits using the format presented in Table 5.4.

Table 5.4. Format of ANOVA for two-way factorial experiment (RCBD)

Source of variation	Df	Mean square (MS)	Expected mean square (EMS)
Genotypes (G)	199	MS_g	$\sigma^2_e + RP\ \sigma^2g + R\ \sigma^2gp$
P – fertilisation (P)	1	MS_p	$\sigma^2_e + RG\ \sigma^2 + R\ \sigma^2gp$
G*E		MS_{gp}	$\sigma^2_e + R\ \sigma^2gp$
Error (E)		MS_e	σ^2_e

σ^2_e = error term; σ^2g = genotypic variance; σ2gp = variance due to genotypes by phosphorus interaction; MS_g = mean square for genotype; MS_p = mean square for phosphorus level; MS_{gp}= mean square for genotype by phosphorus interaction; MS_4 = mean square error

Genetic and phenotypic variances as well as genotypic and phenotypic coefficients of variation were calculated using the following formulae;

University of Ghana http://ugspace.ug.edu.gh

Genotypic variance (σ^2_g) = MS_g-MS_e/r

Error variance (σ^2_e) = MS_e/r; where MS_g and MS_e are the mean squares of the genotypes and error respectively and r is the number of replications.

Phenotypic variance (σ^2_p) = (σ^2_g) + (σ^2_e)

Genotypic and phenotypic coefficients of variation were calculated according to the formulae proposed by Burton (1952). PCV and GCV values greater than 20% were regarded as high, values between 10 and 20% were intermediate, whereas values less than 10% were considered low (Khorgade *et al*., 1985).

$$GCV = \frac{\sqrt{\sigma^2_g}}{x} \times 100; \qquad PCV = \frac{\sqrt{\sigma^2_p}}{x} \times 100$$

ECV (Environmental Coefficient of Variation) = $\sqrt{\sigma^2_e} \times 100/x$

GECV (Genotype by Environment interaction coefficient of variation) = $\sqrt{\sigma^2_{gp}} \times 100 / x$

Where x = sample mean

Broad sense heritability (H^2) was estimated using the formula suggested by Falconer (1989) as follows; $H^2 = \sigma^2_g / \sigma^2_g + \sigma^2_p$; where σ^2_g = genotypic variance and σ^2_p = phenotypic variance.

Pearson's correlation coefficients were estimated using the mean values in each P environment. Hierarchical agglomerative clustering was done using Pearson's dissimilarity matrix. A dendrogram was formed based on unweighted pair group method with arithmetic mean (UPGMA). All mean values were standardized prior to analyses. Correlation and cluster analyses were done using XLSTAT 2017.

University of Ghana http://ugspace.ug.edu.gh

P-uptake [PUp] (mg/plant) was calculated according to Gunes *et al*. (2006) where;

PUp = Stover yield (g) x P concentration in the stover (mg/g).1

P-utilisation efficiency (PUtE) was calculated according to Rose and Wissuwa (2012); where P-utilisation efficiency is the stover yield produced per unit P accumulated in the stover.

PUtE = Stover yield (g) / P-uptake (PUp).

P-tolerance ratios (relative performance) were calculated for each genotype. The mean value of each trait in the low P trial was divided by its corresponding mean value in the optimum P trial for each genotype (Leiser *et al*., 2015). The ratios were calculated for seedling-vigor (SVR), days to flowering (DTFR), plant height (PHR) and grain yield (GYR). Genotypes that scored higher SVR, PHR and GYR and lower DTFR were expected to be better adapted to low-P stress (Leiser *et al*., 2015). The genotypes were ranked for tolerance to low-P stress based on a selection differential where; Selection differential, S = GYR of the genotype – Grand mean (GYR) (Leiser *et al*., 2012). Genotypes were tolerant if the GYR of that genotype was higher than the grand mean whereas inefficient genotypes had GYR values lower than the grand mean (Ozturk *et al*., 2005;Gunes *et al*., 2009). The top 10% P-use efficient genotypes were those that scored the highest selection differentials.

5.2.6.2 Data analysis for field experiment

Analysis of variance for field experiments was performed in two stages. Initially, each P trial (single-environment) was analysed separately to evaluate the differences between the genotypes within each environment. Each trait was analysed with a restricted maximum likelihood (REML) mixed model where genotypes were treated as fixed effects and incomplete blocks were fitted as random effects. Differences between genotypic means across the optimum P and low P trials were

University of Ghana http://ugspace.ug.edu.gh

tested using at two-sided *t* test. Correlations between traits were estimated for each P environment. Subsequently, a combined analysis of variance across the two environments was done where P treatments were treated as fixed and genotypes as random to estimate the genotype-by-P interaction. Genetic and phenotypic variances, genotypic and phenotypic coefficients of variation (GCV and PCV respectively) as well as broad sense heritabilities were estimated using formulae as described for the pot experiment. ANOVA were carried out using SAS 9.2 software (SAS Institute Inc., Cary, NC) whereas correlation analysis and genetic parameters were estimated using XLSTAT 2017.

Phosphorus-uptake and utilisation efficiency parameters were calculated as described by Leiser *et al*., (2012). The parameters are described in Table 5.5.

University of Ghana http://ugspace.ug.edu.gh

Table 5.5. Estimations of P-uptake and utilisation parameters

Trait	Description	Calculation	Unit
GY	Grain yield		t/ha
SY	Stover yield		t/ha
BM	Total biomass yield	GY + SY	t/ha
PCS	P concentration in stover		mg/g
PCG	P concentration in grain		mg/g
PS	P content in stover	PCS x SY	kg/ha
PG	P content in grain	PCG x GY	kg/ha
PBM	P content of total biomass	PS + PG	kg/ha
PHI	P harvest index	PG/PBM	
PUTIL-G	P-utilisation for grain production	GY/PBM	kg/g P
PUTIL-S	P-utilisation for stover production	SY/PBM	kg/g P
PUTIL-BM	P-utilisation for biomass production	BM/PBM	kg/g P

Based on these parameters, the genotypes were classified into four categories as P-uptake efficient, P-utilisation efficient, low-P stress tolerant and low-P stress sensitive.

University of Ghana http://ugspace.ug.edu.gh

5.3 Results

5.3.1. Pot experiment

5.3.1.1. Characteristics of soils in pot experiment

Soil was characterised as sandy clay. The physical and chemical properties of the soil are as follows; Texture (68.4% sand, 7.2% silt and 24.4% clay), pH (5.6), organic carbon (8.2 g/kg), Total N (1.3 g/kg) and CEC (6.1 $cmol_c$/kg). Plant - available P for the optimum P pots was an average of 18.7 mg P /kg of soil whilst that for the low P pots was 4.6 mg P /kg of soil.

5.3.1.2. Genetic variation among the genotypes under contrasting P environments

Highly significant differences ($p<0.001$) were observed among the genotypes for all traits (Table 5.6.1). Interaction between P-environments and genotypes was also significant ($p<0.001$). Grain yield reduced significantly from an average of 81.7 g/plant under optimum P conditions to 48.8 g/plant under low P- stress (Table 5.6.2). The least grain yield in both low P and optimum P environments (22.1 and 38.2 g respectively) was produced by Feterita Gishesh. Grinkan (121.8 g) and MDK (139.7 g) were the highest producers of grain in the low and optimum P environments respectively. Stover yield also decreased from 237.6 to 149.8 g between the two environments as was the case for plant height which decreased from 103 cm to 81 cm. Seedling vigour scores varied between the two environments with a mean of 3.4 and 4.7 in low and optimum P conditions respectively. The trend was reversed for days to anthesis, as the trait increased from 59.8 days under optimum conditions to 62.5 days under stressed conditions. Distribution of all the traits in both P environments is shown in Figure 5.1

Genetic variance among the assessed traits was lowest (0.21) for seedling vigour and highest (17693.66) for grain yield (Table 5.6.3). Similarly, the highest GCV was observed for grain yield

University of Ghana http://ugspace.ug.edu.gh

(66.09), plant height (59.34) and biomass (51.38) whilst seedling vigour and days to flowering exhibited the lowest GCV of 11.4 and 29.27 respectively. Broad sense heritability were intermediate (approximately 0.50) for all the traits except seedling vigour (0.36).

University of Ghana http://ugspace.ug.edu.gh

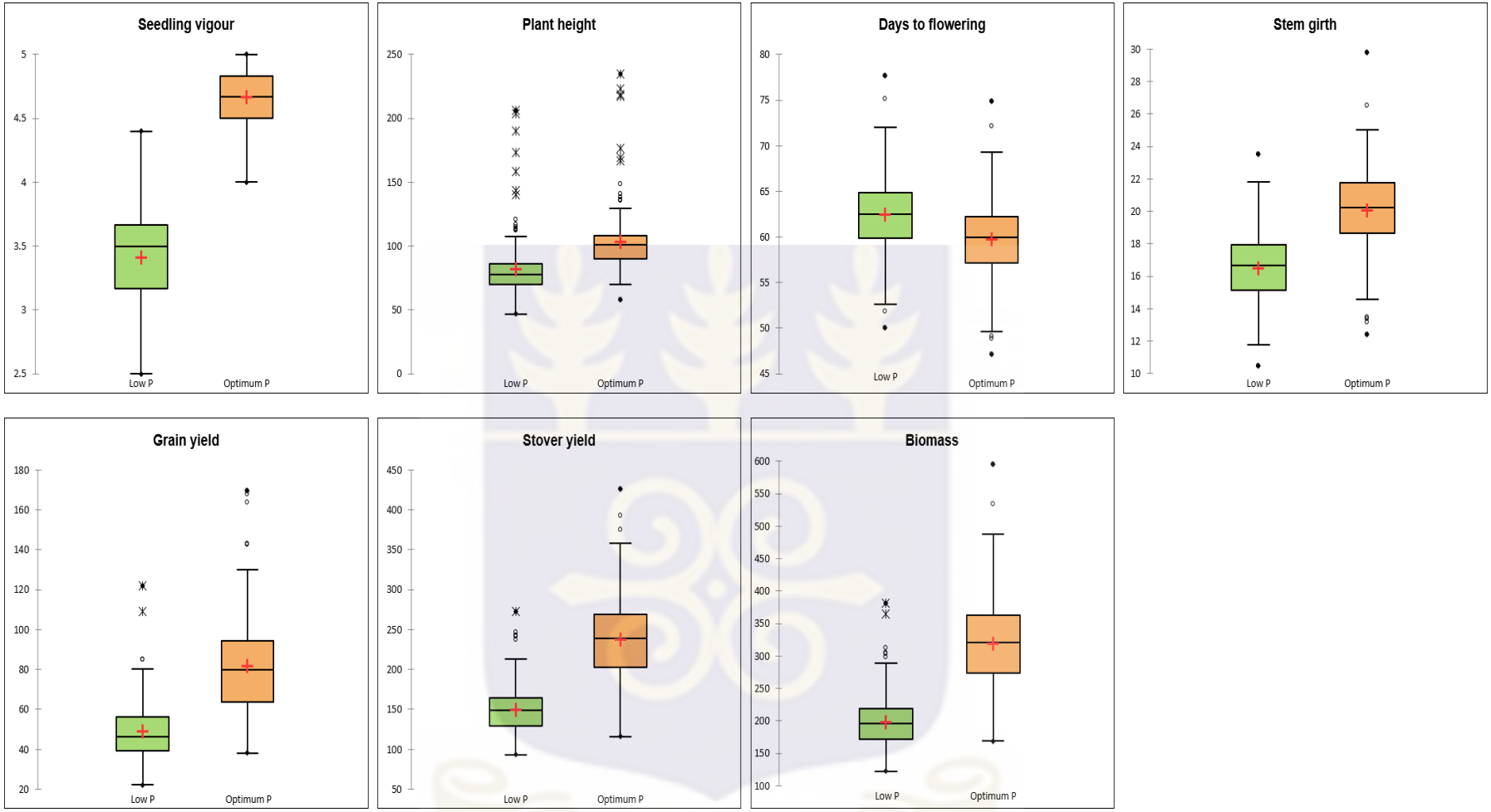


Figure 5.1. Distribution of traits in low and optimum P-environments.

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.1. Analysis of variance under contrasting P environments.

Source of variation	df	SV	PH	DTF	SG	GY	SY	BM
Genotypes (G)	199	0.73**	6031.59**	213.72**	59.88**	3877.70**	19892.09**	36153.16**
P environment (P)	1	942.51**	269985.27**	4400.33**	7738.93**	648554.94**	4625364.20**	8757254.74**
G*P	199	0.44**	96.09**	1.36^{ns}	4.28**	587.10**	3744.72**	5565.28**
Grand mean		4.04	92.40	61.14	18.28	65.31	193.68	258.87
R-square		0.66	0.98	0.92	0.80	0.84	0.89	0.92

** Significant at 0.01 probability level**;** SV = Seedling vigour; PH = Plant height; DTF = Days to flowering; SG= Stem girth; GY= Grain yield per plant; SY = Stover yield per plant; BM = Biomass per plant

Table 5.6.2. Comparison between means of traits in contrasting P environments

	Seedling vigour	Plant height	Days to flowering	Stem girth	Grain yield	Stover yield	Biomass
Optimum P	4.66a	103.01a	59.78a	20.07a	81.73a	237.55a	319.28a
Low P	3.41b	81.80b	62.49b	16.48b	48.85b	149.75b	198.60b

Means followed with different letters in a column are significantly different at $p < 0.05$ in a two-sampled *t* test.

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.3. Heritability, genetic and phenotypic variability of the traits under low-P stress

Trait	σ^2_g	σ^2_p	GCV	PCV	ECV	GECV	Heritability
Seedling vigour	0.21	0.37	11.40	14.97	9.70	3.64	0.367
Days to flowering	105.87	106.86	16.83	16.91	1.63	0.53	0.497
Plant height	3006.57	3015.79	59.34	59.43	3.29	3.89	0.499
Stem girth	28.63	29.94	29.27	29.93	6.28	2.87	0.488
Grain yield/plant	1863.25	1938.85	66.09	67.42	13.31	13.05	0.490
Stover yield/plant	9657.59	9946.05	50.74	51.49	8.77	11.86	0.492
Biomass	17693.66	18076.58	51.38	51.94	7.56	10.93	0.494

Where σ^2_g = genetic variance; σ^2_p = phenotypic variance; GCV = genetic coefficient of variation; PCV = phenotypic coefficient of variation; ECV = Environmental coefficient of variation; GECV = Genotype by Environment interaction coefficient.

University of Ghana http://ugspace.ug.edu.gh

5.3.1.3. Correlation between morpho-agronomic traits and P-tolerance ratios

Plant height was positively correlated with seedling vigour (*r=0.179*) and grain yield (*r = 0.301*) [Table 5.6.4]. Positive and significant ($p<0.05$) correlations were also observed between grain yield and stover yield (*r= 0.602*), days to flowering (*r = 0.380*) and stem girth (*r = 0.234*). Stover yield was also positively correlated to days to flowering was positively (*r = 0.234*) and stem girth (*r = 0.391*). No negative correlations were observed except between the morpho-agronomic traits except between seedling vigour and stem girth (*r = -0.191*).

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.4. Correlation coefficients between morpho-agronomic traits (under low P stress)

Traits	Seedling vigour	Plant height	Days to flowering	Stem girth	Grain yield/plant	Stover yield/plant	Biomass
Seedling vigour	**1**						
Plant height	**0.179**	**1**					
Days to flowering	-0.046	0.116	**1**				
Stem girth	**-0.191**	-0.125	**0.352**	**1**			
Grain yield/plant	-0.056	**0.301**	**0.380**	**0.418**	**1**		
Stover yield/plant	-0.085	**0.256**	**0.234**	**0.391**	**0.602**	**1**	
Biomass	-0.083	**0.297**	**0.307**	**0.439**	**0.798**	**0.962**	**1**

Values in bold are significantly different at $p < 0.05$.

University of Ghana http://ugspace.ug.edu.gh

5.3.1.4. Principal component analyses under contrasting P environments

The contribution of each trait to genetic variation in each P environment was determined using principal component analysis. Under low-P stress conditions, the first three principal components (PC1, PC2 and PC3) explained 77 % of the total variation. PC1, PC2 and PC3 accounted for 45.4%, 18.9 and 12.7% of the total variance respectively (Table 5.6.5). Under optimum P conditions, the first three principal components explained 79% of the total variation and accounted for 47.2, 17.4 and 14.5% of the total variance respectively. In both P environments, yield components (biomass, grain yield and stover yield) were the most important traits for PC1 whereas for PC2, plant height, seedling vigour and stem girth were the most important (Figure 5.2). Days to flowering (0.749) and seedling vigour (0.872) were the highest contributors to the variability in PC3 for low P and optimum P respectively. Contribution of all the traits in PC1 and PC2 are shown in Figure 5.2.

The bi-plots (Figure 5.3) clearly separated the mutant genotypes from the cultivated lines with respect to the assessed traits. In both P conditions, genotypes in quadrant I (such as MDK, Grinkan, MR732 and Mut3864) were characterised by high grain and stover yield. Conversely, genotypes in quadrant III were characterised by lower values in yield. On the other hand, genotypes in quadrant IV comprised early-flowering types such as Mut2902#1, SC35, Mut0393#1.

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.5. Principal components of morpho-agronomic traits in the contrasting P environments

	Low P			Optimum P		
Traits	**PC1**	**PC2**	**PC3**	**PC1**	**PC2**	**PC3**
Seedling vigour	-0.070	**0.589**	**0.503**	-0.028	**-0.323**	**0.872**
Plant height	0.192	**0.642**	-0.076	0.160	**0.723**	**0.362**
Days to flowering	0.287	-0.133	**0.749**	0.282	-0.281	**0.259**
Stem girth	0.334	**-0.456**	0.249	0.361	**-0.490**	-0.167
Grain yield/plant	**0.494**	0.076	-0.023	**0.494**	-0.042	-0.108
Stover yield/plant	**0.477**	0.063	**-0.289**	**0.484**	0.206	0.046
Biomass	**0.542**	0.077	-0.182	**0.534**	0.100	-0.028
Eigenvalue	**3.180**	**1.326**	**0.890**	**3.301**	**1.219**	**1.012**
Variability (%)	**45.432**	**18.945**	**12.711**	**47.152**	**17.408**	**14.455**
Cumulative %	**45.432**	**64.377**	**77.088**	**47.152**	**64.560**	**79.015**

The highest factor loadings are shown in bold.

University of Ghana http://ugspace.ug.edu.gh

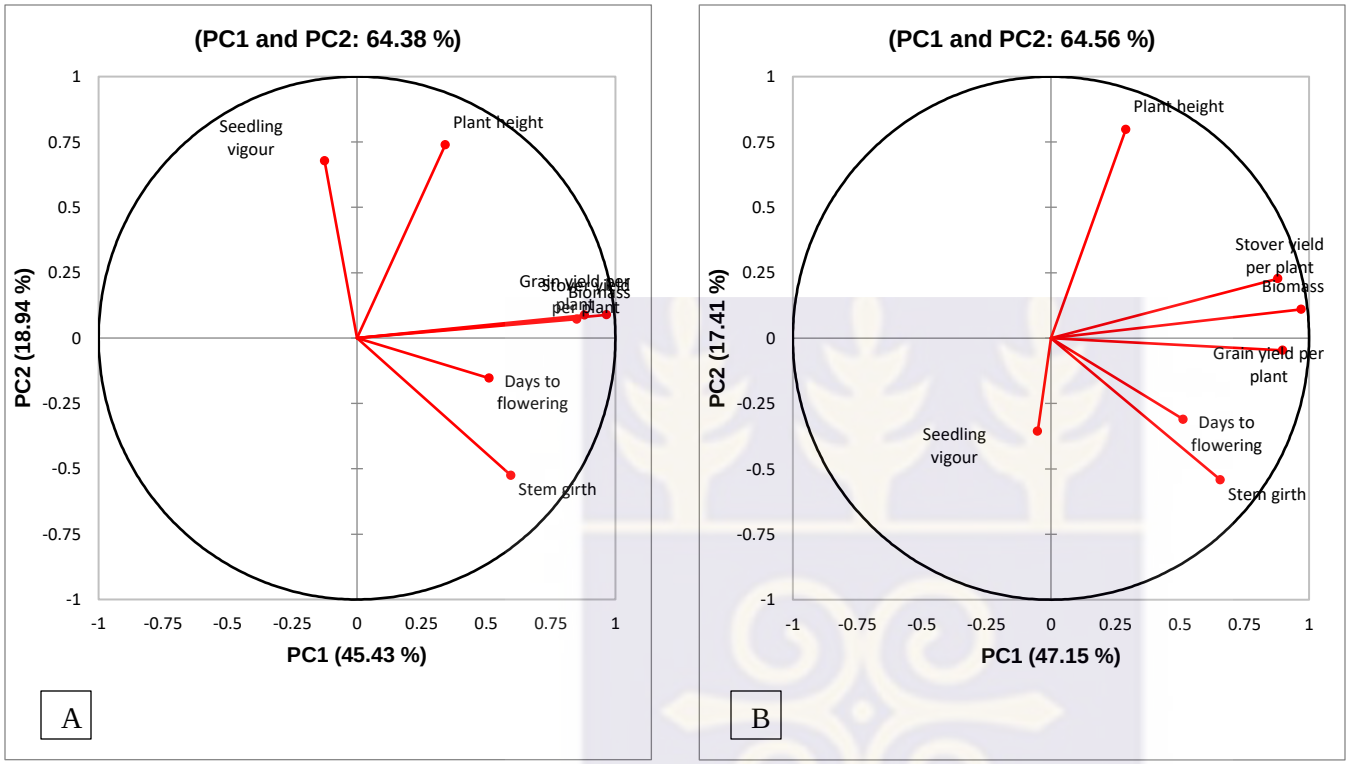


Figure 5.2. Loading plot of PC1 and PC2 showing contribution of morpho-agronomic traits to variability in (A) low P environment and (B) optimum P environment.

University of Ghana http://ugspace.ug.edu.gh

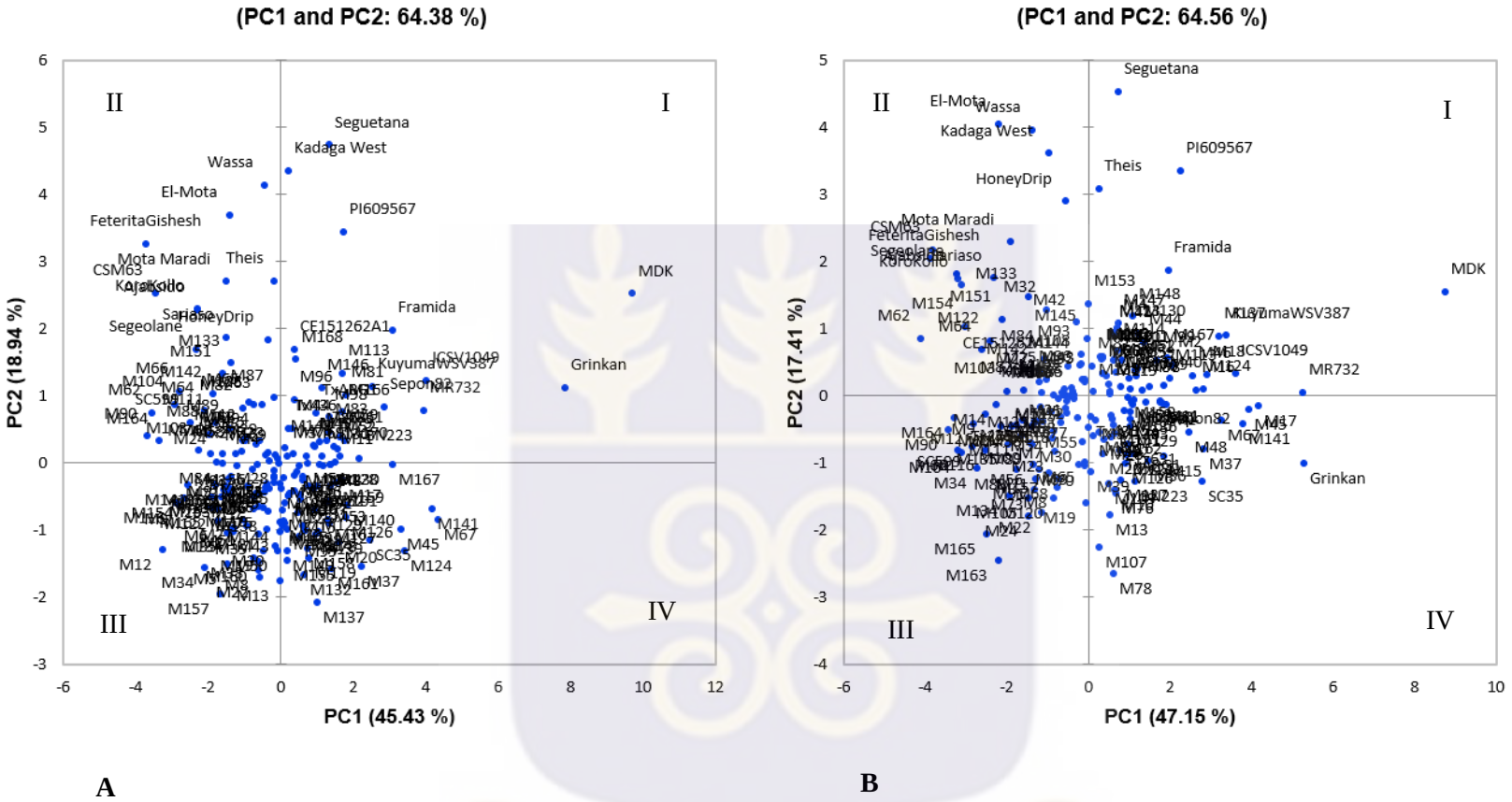


Figure 5.3. Distribution of the 200 genotypes for PC1 and PC2 under (A) low-P and (B) optimum P environments. Names of 200 putative mutants in the bi-plots can be found in Appendix 6.

University of Ghana http://ugspace.ug.edu.gh

5.3.1.5. Variation within the population based on cluster analysis.

Three main clusters (I, II and III) were formed at 49% level of dissimilarity (Figure 5.4). Cluster I contained 65 genotypes, 63 of which were mutant families grouped with two cultivated varieties (Tx631 and SC599). The genotypes in this cluster were the late flowering types (63 days) within the population as well as the shortest in height (71 cm). Average grain yield for this cluster was an intermediate 41 g/plant. Cluster II contained 106 genotypes including cultivated varieties such as Grinkan, MR732, KuyumaWSV387 and CE151262A1. These genotypes were the highest in terms of grain (56 g/plant) and stover yield (164 g/plant) with relatively thicker stems (17 cm). Cluster III contained 29 genotypes. Fourteen of the genotypes included in this cluster were the cultivated varieties such as CSM63, Korokollo, Ajabsido, Honeydrip, Sariaso and Kadaga West. The genotypes in this cluster were the tallest (106 cm) and thinnest (13.5 cm) genotypes in the population. The resulting dendrogram is shown in Figure 5.4. Box plots summarising the means of the various clusters are shown in Figure 5.5.

University of Ghana http://ugspace.ug.edu.gh

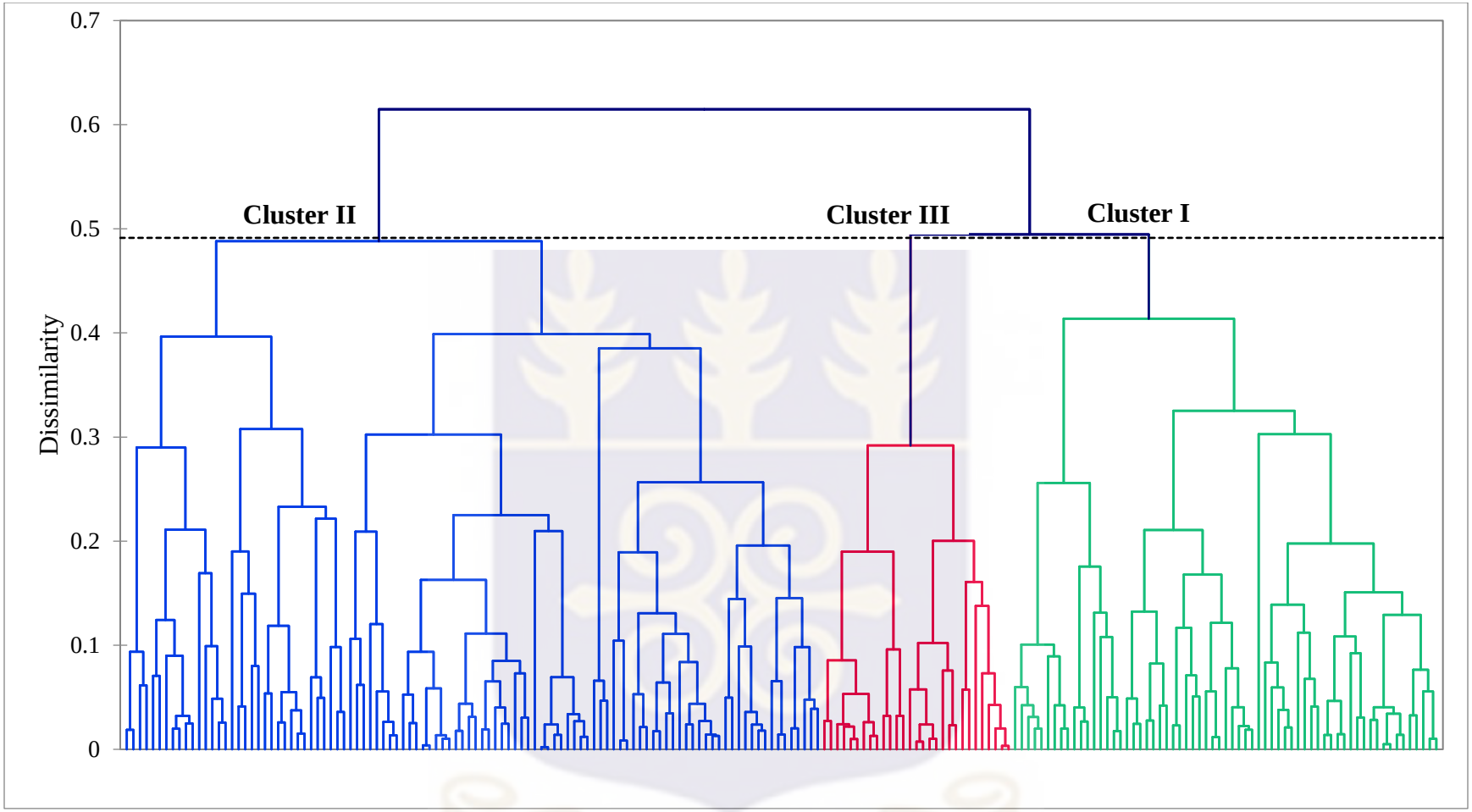


Figure 5.4. Dendrogram of 200 sorghum genotypes derived by UPGMA method (Pearson's dissimilarity matrix) based on standardized data of all morpho-agronomic traits. Details of the members in each cluster can be found in Appendix 7.

University of Ghana http://ugspace.ug.edu.gh

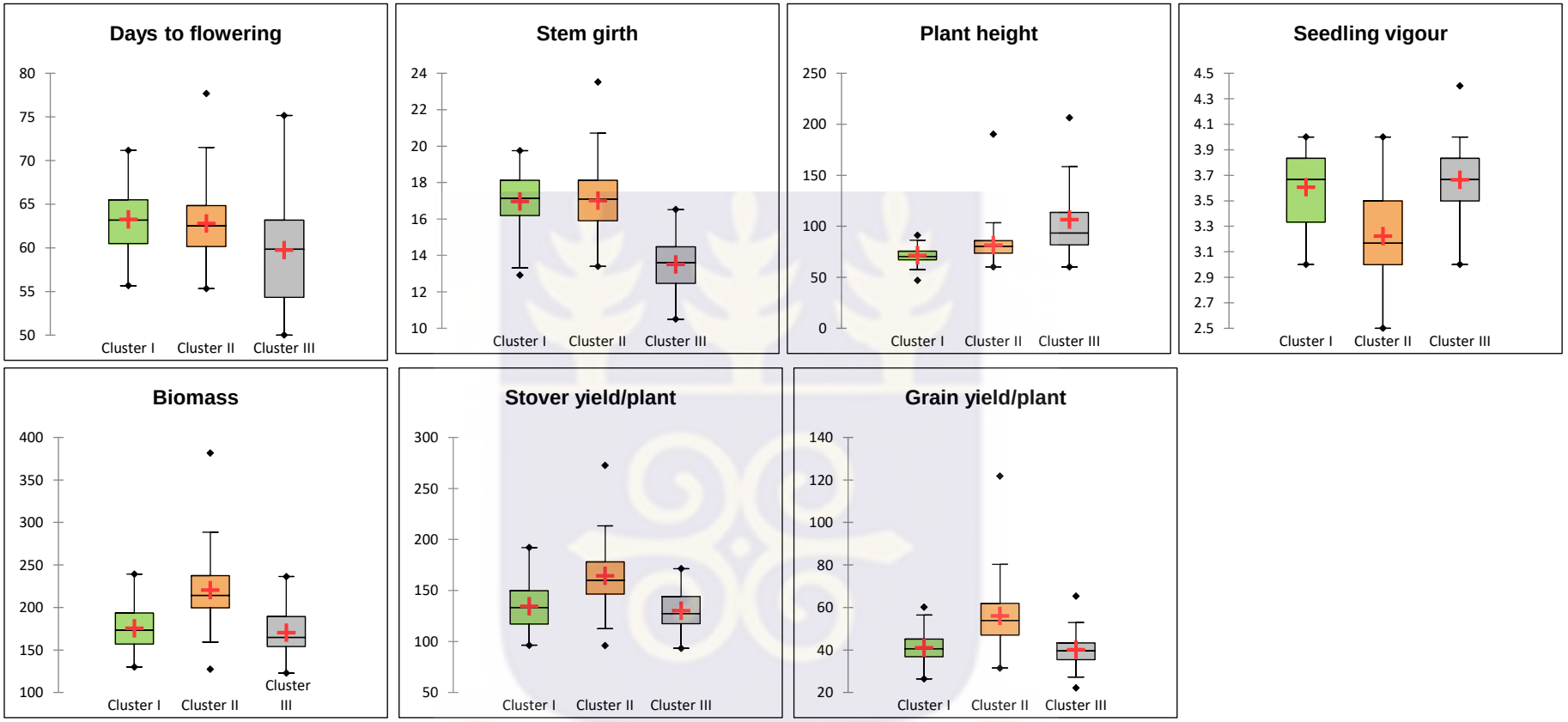


Figure 5.5. Boxplots showing the distribution of traits in each cluster. The upper, median and lower quartiles represent the 75th, 50th and 25th percentiles of the clusters respectively. The vertical lines represent the variation within the clusters. Dots represent outliers.

University of Ghana http://ugspace.ug.edu.gh

5.3.1.6. Relative performance of the genotypes in contrasting P environments.

Relative performance of the genotypes were used as measures or indicators of low-P stress tolerance. P-tolerance ratios were estimated as the genotypic mean of each trait under low P to its corresponding genotypic mean under optimum P conditions. Based on this, seedling vigour ratio (SVR) was lowest (0.55) in Mut1665 and Mut5115 and highest (0.94) in Feterita Gishesh. Average seedling vigour ratio (SVR) within the population was 0.73. The least plant height ratio [PHR] (0.65) was shown in Mut2716 whilst the highest (0.94) was observed in Seguetana. An average of 0.79 was recorded for this trait. The lowest (1.02) days to flowering ratio (DTFR) was observed in six genotypes. These included Mut2856#2, MR732, Mut0460#1, Grinkan, CSM63 and Mut0056. The highest (1.10) was observed in El-Mota. The highest grain yield ratio (0.83) was shown by Wassa whilst the highest stover yield ratio (0.86) was shown by Mut0056. The least P-uptake [PUp] (38.2 mg/plant) was observed in Mut2899#1. Framida had the highest SPU of 142.58 mg/plant. Estimated P-utilisation efficiency (PUtE) was least (1.39) in Korokollo and highest (2.86) in TxARG1.

5.3.1.7. Selection of P-use efficient genotypes

P-use efficient genotypes were selected based on relative performance of the genotype in both P environments with regards to grain yield (grain yield ratio). All genotypes that showed grain yield ratios (GYR) greater than the grand mean (GYR of the population) were categorised as P-use efficient. Estimated grand mean of the grain yield ratios was 0.61. Based on this, 44.5% of the genotypes were P-use efficient whereas 52.5% were inefficient. Three percent showed GYR values equal to the grand mean and were classified as average. Subsequently, the top 10% P-use efficient

University of Ghana http://ugspace.ug.edu.gh

genotypes were selected based on a selection differential; where the selection differential = GYR of the genotype – Grand mean (GYR) of the population. The genotypes with the highest selection differentials were selected. Wassa, Segeolane, Kadaga West, CE151262A1 and Mut4459#2 comprise the first five. The top 10% genotypes are summarised in Table 5.6.6.

Table 5.6.6. Top-ranked (10%) genotypes for grain yield ratio, P-uptake and P-utilisation efficiencies

Rank	Genotypes	GYR	Genotypes	PUp	Genotypes	PUtE
1	Wassa	0.83	Framida	142.58	TxARG1	2.86
2	Segeolane	0.80	ICSV1049	135.26	Mut2854#1	2.78
3	Kadaga West	0.79	Mut3434	128.61	SC35	2.70
4	CE151262A1	0.78	Grinkan	118.91	Mut3003#1	2.63
5	Mut4459#2	0.78	MDK	117.25	Mut0122	2.56
6	Ajabsido	0.78	BN223	115.46	Mut3708	2.56
7	Theis	0.78	Mut4106#1	110.97	Mut3217	2.56
8	Mota Maradi	0.78	Mut2570	106.67	Mut3412	2.56
9	Mut4511	0.76	Mut4155	106.00	Mut3709	2.56
10	SC35	0.75	PI609567	104.41	Tx430	2.56
11	KoroKollo	0.75	Mut0839#2	103.46	Mut3960#1	2.56
12	Grinkan	0.75	Tx631	102.40	Mut2091#1	2.50
13	Seguetana	0.74	Mut3809	102.05	Mut4260-2	2.50
14	Mut3707	0.74	Mut4112	97.61	Mut3808	2.50
15	Mut2854#1	0.74	Mut2359	96.55	Mut2952#1	2.50
16	Mut4156	0.74	Mut4264	95.44	Mut3368	2.50
17	Mut4060#1	0.74	Mut4313-2	94.82	CSM63	2.50
18	Sepon82	0.74	Mut3105	94.55	Mut2899#1	2.50
19	El-Mota	0.73	Mut3005	93.83	Mut2098#1	2.50
20	Mut3708	0.73	Mut0454#1	92.75	Mut3813	2.50

GYR= Grain yield ratio; PUp= P-uptake efficiency; PUtE =P utilisation efficiency

University of Ghana http://ugspace.ug.edu.gh

5.3.2. Field experiment

5.3.2.1. Characteristics of soils in field experiments

Soils of field experiments were characterised as sandy loam belonging to the Toje Series, Rhodic Khandiustalf (Eze, 2008). The physical and chemical properties of the soils in the two P environments were as follows; For the low P field, soil texture (72.3% sand, 18.1% silt and 8.7% clay), pH (5.5), organic carbon (4.1 g/kg), Total N (0.3 g/kg) and CEC (2.9 $cmol_c$/kg). Plant - available P was an average of 5.7 mg P /kg. For the optimum P field, texture (74.4% sand, 19.4% silt and 6.2% clay), pH (5.8), organic carbon (5.0 g/kg), Total N (0.4 g/kg), CEC (3.3 $cmol_c$/kg). Plant - available P was an average of 19.5 mg/kg.

5.3.2.2. Genotypic variation for morpho-agronomic traits in contrasting P environments

Highly significant differences ($p<0.001$) were observed among the genotypes for all morpho-agronomic traits in both P environments (Tables 5.6.7 and 5.6.8). A significant shift in mean values was also observed between the two P-environments. Under low P conditions, days to anthesis decreased from 62 days to 60 days under adequate conditions. For all other traits, mean values increased significantly under optimum conditions. Plant height increased from 80 to 101 cm whereas stover yield increased from 3.5 tonnes/ha in the low P environment to 4.7 tonnes/ha under optimum conditions. Mean grain yield varied almost two-fold between the two environments (0.86 tonnes/ha to 1.69 tonnes/ ha). Within the P-stressed environment, grain yield was least (0.3 tonnes/ha) in CSM63 and Feterita Gishesh and highest (2.2 tonnes/ ha) in Grinkan. Within the mutant population, grain yield under P stress was least (0.4 tonnes/ha) in Mut4313-2, Mut1455#1 and Mut1817-2 and highest (1.5 tonnes/ha) in Mut2572, Mut3108, Mut3419 and Mut2570. On the other hand, under optimum P conditions, Mut1864 produced the least grain yield (0.6 tonnes/ha)

University of Ghana http://ugspace.ug.edu.gh

whereas the highest (3.9 tonnes/ha) was produced by Mut4366. The differences between the test genotypes and the control varieties were also significant for all traits except stem girth and biomass. Details of the analysis of variance for the morpho-agronomic traits in the two P environments are presented in Tables 5.6.7 and 5.6.8. Results of two-sampled t-test comparing the means in the two environments are summarised in Table 5.6.9.

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.7. Analysis of variance for morpho-agronomic traits in low-P stress

Source of variation	Df	SV	DTF	PH	SG	GY	SY	BM	HI
Blocks	19	0.026^{ns}	1.046^{ns}	123.759^{ns}	1.853^{ns}	0.019^{ns}	0.109^{ns}	0.160^{ns}	0.001^{ns}
Entries	199	0.286*	43.223*	1735.983*	7.501*	0.179*	1.339*	1.775*	0.007*
Test genotypes (T)	197	0.207*	19.861*	273.133*	4.645*	0.068*	1.238*	1.553*	0.004*
Controls (C)	1	9.801*	50.625*	82910.130*	572.292*	10.100*	13.225*	47.089*	0.081*
T vs C	1	6.282*	4620.530*	209132.053*	5.370^{ns}	11.961*	9.415*	0.181^{ns}	0.604*
Error	19	0.014	0.625	152.936	1.650	0.010	0.147	0.183	0.001
CV (%)		3.775	1.234	13.269	7.798	10.671	11.402	9.906	9.350

* = significant at $p < 0.01$; ns = non-significant; Df = degrees of freedom; SV= Seedling vigour; DTF = Days to flowering; PH = Plant height; SG = Stem girth; GY = Grain yield; SY = Stover yield; BM = Biomass; HI = Harvest index; CV = Coefficient of variation

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.8. Analysis of variance for morpho-agronomic traits under optimum soil P

Source of variation	Df	SV	DTF	PH	SG	GY	SY	BM	HI
Blocks	19	0.005^{ns}	0.374^{ns}	156.155^{ns}	2.731*	0.023^{ns}	0.102^{ns}	0.180^{ns}	0.0003^{ns}
Entries	199	0.125*	38.081*	3040.360*	11.658*	0.523*	1.588*	3.350*	0.0031*
Test genotypes (T)	197	0.106*	18.368*	602.941*	8.133*	0.362*	1.144*	2.257*	0.0028*
Controls (C)	1	0.169*	84.100*	171858.990*	701.406*	28.224*	90.601*	218.089*	0.0176*
T vs C	1	3.953*	3862.903*	313211.093*	16.280*	4.430*	0.020^{ns}	3.953*	0.0426*
Error	19	0.011	0.521	178.495	1.196	0.029	0.062	0.129	0.0003
CV (%)		2.292	1.170	11.440	5.740	9.710	5.284	5.540	6.1796

* = significant at p < 0.01; ns = non-significant; Df = degrees of freedom; SV= Seedling vigour; DTF = Days to flowering; PH = Plant height; SG = Stem girth; GY = Grain yield; SY = Stover yield; BM = Biomass; HI = Harvest index; CV =Coefficient of variation.

University of Ghana http://ugspace.ug.edu.gh

Table 5.6.9. Comparison between means of traits in low P and optimum P environments

Traits	SV	PH	DTF	SG	GY	SY	BM	HI
Low P	3.02a	80.74a	62.18a	16.38a	0.86a	3.45a	4.31a	0.21a
Optimum P	4.54b	101.31b	59.98b	18.91b	1.69b	4.71b	6.40b	0.26b
$LSD_{0.05}$	1.52	20.57	2.20	2.53	0.83	1.26	2.09	0.06

Means followed with different letters in a column are significantly different at $p < 0.05$. SV= Seedling vigour; PH= Plant height; DTF = Days to flowering; SG= Stem girth; GY= Grain yield; SY= Stover yield; BM= Biomass; HI = Harvest index; LSD= Least significant difference at $p<0.05$.

University of Ghana http://ugspace.ug.edu.gh

5.3.2.3. Genotypic variation for P-use efficiency indicators in contrasting P environments

All P-use efficiency indicators varied significantly ($p < 0.01$) between the genotypes and also between the two P environments (Tables 5.7.1 and 5.7.2). For instance, P concentrations in the grain (PCG), in the stover (PCS), P harvest index (PHI) and P utilisation for grain production (PUTIL-G) were all significantly affected by genotype and the environment. Genotype TxARG1 demonstrated the highest PUTIL-G of 0.71 kg/g P whereas Mut4313-2 had the least (0.17 kg/g P). Stover yield, P harvest index, P content of biomass increased significantly in the adequate P environment in comparison to low P (Table 5.7.3). Lowest PCG values varied from 0.60 mg/g in Kadaga West to 0.81 mg/g in Mut001 in low and optimum P soils respectively. The highest PCG in both P environments was shown by Sariaso (1.29 mg/g and 1.57 mg/g). At low P, PHI ranged from 0.13 in Mut3612 to 0.53 in Mut3779 whereas in optimum P, the trait ranged from 0.19 in Mut4512 to 0.58 in Mut3218. Under low P stress, there were no significant differences between the test genotypes and the control.

In a combined ANOVA for the two P environments, genotype x environment interactions were highly significant for seedling vigour, days to flowering, grain yield, stover yield and biomass (Table 5.7.4). However, genotype x environment interaction was not significant for plant height and stem girth in the combined ANOVA.

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.1. Analysis of variance for P-uptake and use efficiency indicators in low P stress

Source of variation	Df	PCG	PCS	PG	PS	PBM	PHI	PUTIL-G	PUTIL-S	PUTIL-BM
Blocks	19	0.002^{ns}	0.002^{ns}	0.030^{ns}	0.075^{ns}	0.122^{ns}	0.002^{ns}	0.003^{ns}	0.008^{ns}	0.014^{ns}
Entries	199	0.009*	0.005*	0.166*	0.406*	0.741*	0.010*	0.015*	0.065*	0.050*
Test genotypes (T)	197	0.005*	0.005*	0.045*	0.380*	0.541*	0.006*	0.011*	0.039*	0.036*
Controls (C)	1	0.778*	0.018*	14.340*	5.027*	36.214*	0.218*	0.000^{ns}	1.576*	1.624*
Tests vs Controls	1	0.000^{ns}	0.023*	9.808*	0.8878*	4.770*	0.539*	0.858*	3.829*	1.056*
Error	19	0.002	0.001	0.023	0.081	0.123	0.001	0.003	0.005	0.009
CV (%)		5.929	7.569	20.157	17.558	14.762	11.402	12.100	5.016	5.111

* = significant at p<0.01; ns= non-significant; Df = degrees of freedom; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; CV = Coefficient of variation.

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.2. Analysis of variance for P- uptake and use efficiency indicators under optimum soil P conditions

Source of variation	Df	PCG	PCS	PG	PS	PBM	PHI	PUTIL-G	PUTIL-S	PUTIL-BM
Blocks	19	0.002^{ns}	0.001^{ns}	0.028^{ns}	0.123^{ns}	0.174^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.002^{ns}
Entries	199	0.019*	0.010*	0.716*	1.028*	2.917*	0.005*	0.005*	0.027*	0.028*
Test genotypes (T)	197	0.017*	0.009*	0.465*	0.698*	1.772*	0.005*	0.005*	0.023*	0.025*
Controls (C)	1	0.339*	0.155*	45.518*	66.487*	221.841*	0.018*	0.004*	0.538*	0.635*
T vs C	1	0.077*	0.004*	5.254*	0.573*	9.304*	0.031*	0.052*	0.144*	0.026*
Error	19	0.002	0.001	0.049	0.072	0.173	0.001	0.004	0.002	0.002
CV (%)		4.460	4.151	11.410	8.643	8.268	5.650	6.018	4.550	3.366

* = significant at p<0.01; ns= non-significant; Df = degrees of freedom; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; CV = Coefficient of variation.

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.3. Comparison between means of traits in low P and optimum P environments

	PCG	PCS	PG	PS	PBM	PHI	PUTIL-G	PUTIL-S	PUTIL-BM
Low P	0.78a	0.47a	0.67a	1.65a	2.31a	0.30a	0.39a	1.50a	1.89a
Optimum P	1.11b	0.65b	1.87b	3.07b	4.94b	0.38b	0.34b	0.98b	1.32b
$LSD_{0.05}$	0.33	0.18	1.21	1.42	2.63	0.08	0.05	0.52	0.57

Means followed with different letters in a column are significantly different at $p < 0.05$. PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; LSD = Least significant difference at $p<0.05$.

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.4. Combined analysis of variance for morpho-agronomic traits

Sources of variation	Df	SV	PH	DTF	SG	GY	SY	BM
Genotype	199	0.34***	4704.00***	83.30***	19.20***	0.60***	2.58***	4.60***
Environment	1	269.25***	66231.00***	675.40***	793.30***	75.92**	216.88***	54.84***
G*E	199	0.15***	115.00^{ns}	1.70***	0.80^{ns}	0.12***	0.59***	0.80***
Environment (Block)	1	0.11**	244.00^{ns}	3.10*	1.90^{ns}	0.14**	0.19^{ns}	0.80*
Error	75	0.01	152.00	0.60	1.90	0.02	0.10	0.20

***, **, * = significant at p < 0.001; 0.01; 0.1 respectively; ns = non-significant; Df = degrees of freedom; SV= Seedling vigour; DTF = Days to flowering; PH = Plant height; SG = Stem girth; GY = Grain yield; SY = Stover yield; BM = Biomass; HI = Harvest index; CV =Coefficient of variation.

Table 5.7.5. Combined analysis of variance for P- uptake and use efficiency traits

* = significant at p<0.01; Df = degrees of freedom; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; CV = Coefficient of variation.

Sources of variation	Df	HI	PCG	PCS	PG	PS	PMB	PHI	PUTIL-G	PUTIL-S	PUTIL-BM
Genotype	199	0.0082	0.0220	0.0130	0.7200	1.2500	3.2000	0.0122	0.0169	0.0720	0.0700
Environment	1	0.1311	12.4980	3.5970	166.7000	259.3700	841.8000	0.4564	0.4957	27.2690	35.2300
G*E	199	0.0039	0.0080	0.0030	0.1900	0.3000	0.7000	0.0042	0.0052	0.0260	0.0200
Environment (Block)	1	0.0002	0.0010	0.3930	0.0900	0.0400	0.2000	0.0015	0.0002	0.0180	0.0100
Error	75	0.0006	0.0020	0.0010	0.0300	0.0900	0.1000	0.0011	0.0017	0.0040	0.0100

University of Ghana http://ugspace.ug.edu.gh

5.3.2.4. Heritability and genotypic coefficient of variation within the population

Under low P-stress, heritability ranged from 0.57 for P concentration in the stover to 0.97 for days to flowering (Table 5.7.6). Heritability estimates tended to be higher under optimum conditions where it ranged from 0.77 for P concentration in the grain to 0.97 for days to anthesis. No low GCV values (< 10) were observed for the traits in the low P environment. In this environment, GCV ranged from 10.2 for days to anthesis to 48.8 for P content of the grain. Under optimum conditions however, low GCV (7.4) was observed for seedling vigour. The highest GCV (45.8) was observed for plant height.

Table 5.7.6. Estimates of broad-sense heritability and genotypic coefficient of variation in low P trials

	H^2		GCV (%)	
Traits	**Low P**	**Optimum P**	**Low P**	**Optimum P**
SV	0.91	0.84	16.86	7.35
DTF	0.97	0.97	10.19	9.94
PH	0.84	0.89	42.69	45.81
SG	0.64	0.81	14.69	16.98
GY	0.89	0.90	43.24	40.18
SY	0.80	0.92	32.45	26.21
BM	0.81	0.93	29.24	27.79
HI	0.87	0.82	35.69	19.84
PCG	0.63	0.77	10.73	11.53
PCS	0.57	0.87	12.35	14.78
PG	0.76	0.87	48.82	42.11
PS	0.67	0.87	35.21	31.58
PBM	0.72	0.89	33.13	32.91
PHI	0.76	0.82	28.76	18.01
PUTIL-G	0.72	0.85	27.38	19.11
PUTIL-S	0.85	0.87	16.96	16.32
PUTIL-BM	0.69	0.87	10.84	12.38

H^2 = broad sense heritability; GCV (%) = genetic coefficient of variation

University of Ghana http://ugspace.ug.edu.gh

5.3.2.5. Correlation between morpho-agronomic traits and P-use efficiency indicators in contrasting soil-P environments

In both P environments, grain yield was positively correlated with stover yield (*r = 0.408*; *r = 0.562*), P content in the grain (*r= 0.954*; *r = 0.947*) and P harvest index (*r = 0.449*; *r = 0.608*) [Tables 5.7.7 and 5.7.8] but exhibited a negative correlation with P utilisation for stover production (*r = -0.394*; *r= -0.494*). No significant correlation was observed between grain yield and P concentration in the grain. On the other hand, whereas the relationship between stover yield and harvest index was significant (*r= -0.540*) in low P soils, there was no significant relationship between the two traits in optimum P soils. This was also the case for the relationship between stover yield and P utilisation for grain yield as well as between harvest index and P concentration in the grain (Tables 5.7.7 and 5.7.8).

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.7. Correlation between morpho-agronomic traits and P-use efficiency indicators under low soil P conditions

Traits	GY	SY	BM	HI	PCG	PCS	PG	PS	PBM	PHI	PUTIL -G	PUTIL -S	PUTIL -BM
GY	**1**												
SY	**0.408**	**1**											
BM	**0.576**	**0.981**	**1**										
HI	**0.507**	**-0.54**	**-0.378**	**1**									
PCG	-0.025	**0.173**	**0.149**	**-0.193**	**1**								
PCS	0.026	0.121	0.114	-0.131	**0.149**	**1**							
PG	**0.954**	**0.464**	**0.616**	**0.411**	**0.259**	0.066	**1**						
PS	**0.379**	**0.908**	**0.893**	**-0.501**	**0.201**	**0.503**	**0.443**	**1**					
PBM	**0.596**	**0.894**	**0.926**	**-0.297**	**0.244**	**0.439**	**0.663**	**0.965**	**1**				
PHI	**0.449**	**-0.499**	**-0.352**	**0.911**	0.024	**-0.437**	**0.420**	**-0.587**	**-0.367**	**1**			
PUTIL-G	**0.432**	**-0.534**	**-0.387**	**0.937**	**-0.307**	**-0.448**	**0.309**	**-0.619**	**-0.426**	**0.939**	**1**		
PUTIL-S	**-0.394**	**0.311**	**0.196**	**-0.639**	**-0.139**	**-0.638**	**-0.402**	-0.006	-0.123	**-0.397**	**-0.343**	**1**	
PUTIL-BM	**-0.169**	0.026	-0.012	**-0.142**	**-0.317**	**-0.917**	**-0.246**	**-0.352**	**-0.366**	0.111	**0.201**	**0.851**	**1**

GY= Grain yield; SY= Stover yield; BM= Biomass; HI = Harvest index; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; Values in bold are significant at $p < 0.05$.

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.8. Relationship between yield components and P-use efficiency indicators under optimum soil P conditions

Traits	GY	SY	BM	HI	PCG	PCS	PG	PS	PMB	PHI	PUTIL-G	PUTIL-S	PUTIL-BM
GY	**1**												
SY	**0.562**	**1**											
BM	**0.803**	**0.944**	**1**										
HI	**0.732**	-0.119	**0.206**	**1**									
PCG	-0.038	-0.131	-0.110	0.075	**1**								
PCS	0.059	0.029	0.045	0.023	**0.442**	**1**							
PG	**0.947**	**0.489**	**0.730**	**0.735**	**0.264**	**0.190**	**1**						
PS	**0.498**	**0.839**	**0.803**	-0.083	0.103	**0.552**	**0.503**	**1**					
PMB	**0.803**	**0.786**	**0.887**	**0.324**	**0.201**	**0.450**	**0.834**	**0.897**	**1**				
PHI	**0.608**	**-0.165**	0.123	**0.903**	**0.215**	**-0.271**	**0.658**	**-0.282**	**0.156**	**1**			
PUTIL-G	**0.595**	-0.091	**0.171**	**0.815**	**-0.353**	**-0.508**	**0.467**	**-0.335**	0.025	**0.830**	**1**		
PUTIL-S	**-0.494**	0.089	-0.133	**-0.676**	**-0.567**	**-0.685**	**-0.650**	**-0.287**	**-0.516**	**-0.494**	**-0.145**	**1**	
PUTIL-BM	**-0.211**	0.045	-0.051	**-0.287**	**-0.703**	**-0.886**	**-0.418**	**-0.426**	**-0.486**	-0.106	**0.306**	**0.898**	**1**

GY= Grain yield; SY= Stover yield; BM= Biomass; HI = Harvest index; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; Values in bold are significant at $p < 0.05$.

University of Ghana http://ugspace.ug.edu.gh

5.3.2.6. Differences between mutants and cultivated varieties for morpho-agronomic traits

A comparison between the top-ranked mutant lines and the top-ranked cultivated genotypes (in terms of P utilisation for grain production) revealed differences for several P-use efficiency traits. Stover yield was significantly ($p < 0.0l$) lower in the mutants compared to the cultivated types. On the other hand, in terms of P utilisation for grain production and P harvest index, the mutants exhibited significantly ($p < 0.0l$) higher mean values compared to the cultivated varieties. In general, higher values for P-uptake traits were observed among the cultivated genotypes whereas the mutants had higher values for utilisation traits. Within the mutant population, Mut2572 showed the highest stover yield and utilisation of P for grain yield production. In terms of P concentration in the grain, the top-ranked mutant was Mut1771-2. No significant differences were observed between the two groups for grain yield as well as P concentration in the grain and stover. The differences between the two groups for the respective traits are shown in Figure 5.7. The highest-ranking mutants and cultivated types for the various categories are summarized in Table 5.7.9.

University of Ghana http://ugspace.ug.edu.gh

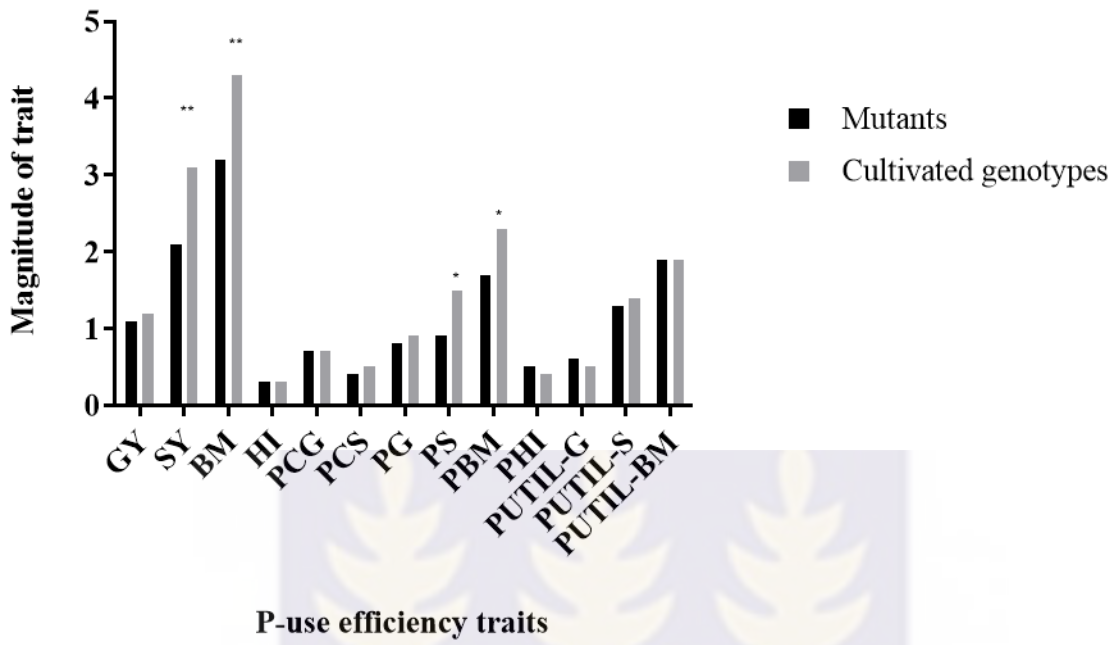


Figure 5.6. Comparison between highest ranking mutants and cultivated genotypes for P-use efficiency traits in low P environment. GY= Grain yield; SY= Stover yield; BM= Biomass; HI = Harvest index; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; Where indicated, the two groups are significantly different at at 0.5 (*) and 0.01 (**) probability levels.

University of Ghana http://ugspace.ug.edu.gh

Table 5.7.9. Highest-ranking mutants and cultivated genotypes for yield and PUE indicators

	Traits	Mutants	Cultivated genotypes	Overall
Yield	GY	Mut2572	Grinkan	Grinkan
	SY	Mut0538	MDK	MDK
	BM	Mut0538	MDK	MDK
P-uptake	PCG	Mut1771-2	Sariaso	Sariaso
	PCS	Mut4264	Korokollo	Korokollo
	PG	Mut3108	Grinkan	Grinkan
	PS	Mut3434	ICSV1049	ICSV1049
	PBM	Mut3434	ICSV1049	ICSV1049
P-utilisation	PHI	Mut2572	TxARG1	Mut2572
	PUTIL-G	Mut2572	TxARG1	TxARG1
	PUTIL-S	Mut3708	SC35	Mut3708
	PUTIL-BM	Mut3708	SC35	Mut3708
P-stress tolerance	SVR	Mut0317	SC599	Mut0317
	DFR	Mut0056	Sariaso	Mut0056
	PHR	Mut2856#2	SC35	Mut2856#2
	SYR	Mut4107#1	Framida	Mut4107#1

GY= Grain yield; SY= Stover yield; BM= Biomass; HI = Harvest index; PCG= P concentration in the grain; PCS= P concentration in the stover; PG= P content of grain; PS= P content of stover; PBM = P content of biomass; PHI= P harvest index; PUTIL-G = P utilisation for grain production; PUTIL-S = P utilisation for stover production; PUTIL-BM = P utilisation for biomass production; SVR= Seedling vigour ratio; DFR= Days to flowering ratio; PHR = Plant height ratio; SYR= Stover yield ratio.

University of Ghana http://ugspace.ug.edu.gh

5.3.2.7. Selection of low soil P-stress tolerant and sensitive genotypes

Under optimum P conditions, the genotypes with the highest grain yield were MDK, MR732, Mut1253 and KuyumaWSV387 with average grain yield of 3.7, 3.4, 3.5 and 2.8 tonnes/ha respectively. In the low-P environment, the genotypes with the highest grain yield were Grinkan, ICSV1049, MDK and Mut2572 with 1.9, 1.8, 1.6 and 1.5 tonnes/ha respectively (Table 5.8.1). However, identification of P-stress tolerant and sensitive genotypes were based on the relative performance of the genotypes in the contrasting P environments (grain yield ratios - GYR). Based on this, the five highest performing varieties were Theis, El-Mota, Grinkan, Mota Maradi and Framida whereas for the mutant population, Mut3412, Mut4017, Mut0460#1, Mut4156 and Mut4218 were the best-performing (Table 5.). In general the mutants showed higher tolerance to low P stress in terms of GYR; GYR for the best performing varieties ranged from 0.65 to 0.74 whereas among the mutants the ratio ranged from 0.82 to 0.93. Least performing varieties included Seguetana, Tx430, PI609567, CSM63 and Sepon82. Among the mutants, most-sensitive types werMut3003#1, Mut3008, Mut1455#1, Mut5115 and Mut4313-2. GYR for the most-sensitive varieties were higher (0.34 to 0.38) compared to GYR for most-sensitive mutants (0.24 to 0.28).

University of Ghana http://ugspace.ug.edu.gh

Table 5.8.1. Top-ranked genotypes (grain yield) in low-P soil and their performance in optimum-P soil

Genotype	GY Low P	Rank Low P	GY Optimum P	Rank Optimum P	GYR (PUE)	Rank (PUE)
Grinkan	1.88	1	2.74	13	0.69	33
ICSV1049	1.75	2	3.92	1	0.45	144
MDK	1.57	3	3.70	2	0.42	153
Mut2572	1.52	4	2.53	19	0.60	70
Mut3108	1.47	5	2.30	35	0.64	50
Mut3419	1.46	6	2.06	52	0.71	27
Mut2570	1.45	7	2.59	18	0.56	81
MR732	1.42	8	3.40	3	0.42	155
Mut2616	1.40	9	1.80	77	0.78	12
Mut0988	1.40	10	2.40	24	0.58	74
Grand mean	0.86		1.69			

GY = Grain yield; GYR = Grain yield ratio; PUE = P-use efficiency.

University of Ghana http://ugspace.ug.edu.gh

Table 5.8.2. Low-P stress tolerant and sensitive genotypes within the population

	Tolerant genotypes			Sensitive genotypes		
Rank	Genotype	GYR	Selection differential	Genotype	GYR	Selection differential
1	Mut3412	0.93	0.40	Mut3003#1	0.24	-0.29
2	Kadaga West	0.88	0.35	Mut3008	0.25	-0.28
3	Mut4017	0.85	0.32	Mut1455#1	0.26	-0.27
4	Mut0460#1	0.83	0.30	Mut5115	0.26	-0.27
5	Mut4156	0.83	0.30	Mut4313-2	0.28	-0.25
6	Mut4218	0.82	0.29	Mut2954#1	0.29	-0.24
7	Mut2850#1	0.81	0.28	Mut2857#1	0.29	-0.24
8	Mut0001	0.80	0.27	Mut1817-2	0.30	-0.23
9	Mut4512	0.79	0.26	Mut1864	0.30	-0.23
10	Mut3160	0.78	0.25	Mut3813	0.30	-0.23
11	Mut3663	0.78	0.25	Mut3760#2	0.32	-0.21
12	Mut2616	0.78	0.25	Mut2205#2	0.32	-0.21
13	Mut3864	0.78	0.25	Mut1769	0.33	-0.20
14	Mut4060#1	0.77	0.24	Mut3659	0.34	-0.19
15	Mut3057	0.76	0.23	Mut2950#1	0.34	-0.19
16	Theis	0.74	0.21	Seguetana	0.34	-0.19
17	Mut3112	0.74	0.21	Tx430	0.35	-0.18
18	Mut4511	0.74	0.21	Mut3217	0.35	-0.18
19	Mut4308	0.73	0.20	Mut1253	0.36	-0.17
20	Mut3105	0.73	0.20	PI609567	0.36	-0.17

GYR= Grain yield ratio.

University of Ghana http://ugspace.ug.edu.gh

5.4 Discussion

Average available-P levels of the low-P environment in this study was 4.6 and 5.7 mg P /kg for the pot and field experiments respectively. According to Doumbia *et al*. (1993), plant-available P in sorghum-cultivating regions of West Africa is generally below 10 mg P /kg of soil. Thus, the P-deficient soils used in this study were fairly representative of the low-input systems of smallholder sorghum farmers in the sub-region. The available P content of the P-deficient soils were also below the critical P threshold for optimum sorghum growth (7 mg P/kg) whereas in the optimum P soils, available P content of 18.7 and 19.5 mg P/ kg indicate adequate supply of P (Manu *et al*., 1991; Doumbia *et al*., 2003. Leiser *et al*. (2012) report similar values in studies aimed at selecting sorghum genotypes in contrasting P environments.

The large decreases in plant height, grain yield and stover yield in the low-P environments compared to optimum P conditions indicate that the two P environments used in the study were sufficiently different for levels of available P (Rose and Wissuwa, 2012). In sorghum, as well as in other crops, such decreases in plant height, grain and stover yield, delays in flowering and poor seedling establishment in P-deficient soils compared to optimum P soils have been reported (Chen *et al*., 2008; Parentoni *et al*., 2010; Leiser *et al*., 2012). According to Leiser *et al*. (2012), selection based on the differences in these traits in contrasting P environments is appropriate for identifying P-use efficient genotypes.

The results also indicated considerable genotypic variation for P-use efficiency was established within the mutagenised population. The higher genotypic variation (GCV) values observed for P-uptake traits compared to P utilisation traits has also been reported by Wissuwa *et al*. (1998). In general, the genotypic variation for PUE was higher under low P conditions compared to optimum conditions. According to Wissuwa and Ae (2001), this enables better selections under low P

University of Ghana http://ugspace.ug.edu.gh

conditions. Relative grain yield under the two P environments was quite high for several genotypes including Mut3412, Kadaga West and Mut4017 which suggests sufficiently good adaptation to soil P deficiency. The performance of Kadaga West might be attributed to years of cultivation and selection under low-input conditions (Buah *et al*., 2012). On the other hand, significant increases in grain and biomass yield between the two environments indicates that most of the genotypes were quite responsive to P fertilisation. For example, genotypes such as Grinkan, ICSV1049, Mut2572, and Mut3108, although not categorised among the most tolerant genotypes, were the highest-ranking in terms of grain yield under optimum P conditions. This reflects the impressive response of these genotypes to adequate nutrient supply. The observation confirms that adequate amounts of the nutrient is required for maximum growth and productivity of sorghum which in turn corroborates opinions that P-use efficient genotypes must be used to complement fertiliser application (Gemenet *et al*., 2016). On the other hand, several inefficient and sensitive genotypes were identified within the population which showed large losses in grain yield under no P fertilisation with yields ranging from 0.3 to 2.2 tonnes/ha. Such yield levels are within the range reported for smallholders in Ghana and West Africa as a whole and reflects the low grain yield recorded in farmers' fields across Ghana and many parts of West Africa (Atokple, 2010; FA0, 2010).

A comparison between the top-ranked mutant lines and the top-ranked cultivated genotypes revealed higher P-uptake efficiency among the cultivated genotypes whereas the mutagenised lines were generally better at utilising P for grain production. According to Manske *et al*. (2002) and Rose and Wissuwa (2012), P-utilisation efficiency is likely to increase with harvest index, an observation which has been reported in cereals such as wheat and rice. Thus, the higher harvest index of the mutant genotypes might account for increased P-utilisation efficiency within the

University of Ghana http://ugspace.ug.edu.gh

mutagenised population. On the other hand, the more efficient P acquisition among the cultivated varieties might be due to decades of selections by farmers (Leiser *et al*., 2012). Higher P-uptake has been linked with improved seedling establishment in low P soils; this might also account for the slightly higher seedling vigour scores observed among the cultivated genotypes (White and Veneklaas, 2012).

The use of relative performance as a strategy to select for tolerance to P-deficient conditions has been shown by Leiser *et al*. (2012b). This is based on the fact that P deficiency causes marked decreases and delays in sorghum growth and development (Sahrawat *et al*., 1995). For instance, P availability at sowing affects early plant development or seedling vigour (Grant *et al*., 2002). It is likely that a higher grain P content of the grain in the cultivated varieties compared to the mutant lines contributed to the high seedling vigour ratios of the cultivated types. Unfortunately, selecting for increased grain P content although beneficial for improved plant establishment has been implicated in mining large amounts of soil P (Rose and Wissuwa, 2012; White and Veneklaas, 2012).

In this study, high grain yield ratios (GYR) were used as a selection criterion to identify genotypes with better tolerance to low P-stress. This form of selection can increase specific adaptation to soil P deficiency as only genotypes that perform relatively well in both environments are selected as tolerant (Lesier *et al*., 2015). However, Blum (2005) suggests that GYR as a selection criterion can lead to lower yield potential. Similar observations were made in this study. The cultivation of PUE genotypes may be less advantageous if the genotypes are inherently low yielding. Thus, it might be important for breeders to select for both high grain yield and PUE. In this case, Grinkan might be more beneficial on farmers' fields whereas the P-use efficient Mut3412 and Kadaga might be more useful as PUE parents in breeding programmes. Selection for earlier days to

University of Ghana http://ugspace.ug.edu.gh

flowering in low-input systems may be useful in production systems where drought and soil P deficiency are major constraints. Although delays in flowering time under inadequate nutrient conditions might be inevitable, genotypes that flower relatively earlier might reduce risks associated with early cessation of rain (Dingkuhn *et al*., 2006).

The positive relationship between P content of the grain, P harvest index and P utilisation for grain production in the low P field suggest that simultaneous selections for these traits is possible (Leiser *et al*., 2014). A very strong correlation was also observed between harvest index and P utilisation for grain production, a phenomenon which has been reported by Rose and Wissuwa (2012). Negative correlations between P concentration in the stover (PCS) and grain yield have also been reported by Lesier *et al*., (2014) which suggest that high concentrations of P in the stover did not result in a corresponding gain in grain yield.

5.6 Conclusions

Phosphorus-uptake and P-utilisation efficiencies was influenced by genotype, P environment and their interaction. Although inadequate supply of P significantly reduced grain and stover yields in all the genotypes, considerable variation for yield still exists among the 200 genotypes under low soil P conditions. Grinkan and MDK were the highest producers of grain and stover. On the whole, P-uptake efficiency was higher among the cultivated genotypes than in the mutant varieties. On the other hand, the mutagenised lines showed better utilisation of P. The top-ranked putative mutants with regards to P-uptake were Mut1771-2, Mut4264, Mut3108 and Mut3434 whereas among the cultivated varieties, Sariaso, Korokollo, Grinkan and ICSV1049 were the most efficient at P-acquisition. In general, Mut2572, TxARG1 and Mut3708 were the most-efficient genotypes

University of Ghana http://ugspace.ug.edu.gh

in terms of utilisation. The mutagenised lines also showed higher tolerance to low-P stress (relative grain yield) compared to the cultivated types. Overall, the most tolerant genotypes were Mut3412, Kadaga West, Mut4017, and Mut0460#1. Mut3003#1, Mut3008, Mut1455 and Mut5115 were the most sensitive types. New sources of P-use efficiency were identified in the mutagenised population. There is potential to exploit the genotypic variability observed within the population for further breeding work either through advancement of the mutagenised lines or as parents in recombinant breeding programmemes.

University of Ghana http://ugspace.ug.edu.gh

CHAPTER SIX

6.0 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Sorghum is an important crop both as a source of food and income among smallholder farmers in the Talensi-Nabdam and Binduri districts of Ghana. However, its production is faced with numerous constraints including drought, limited tractor services for land preparation and declining soil fertility. Strategies to improve productivity of the crop on marginal soils such as the application of fertilisers are largely unexploited due to high cost of mineral fertilisers on rural markets, untimely access to the commodity and limited availability of organic alternatives. On the other hand, farmers' perceptions of the low fertiliser requirements of the crop as well as uncertainties of maximum returns on fertiliser application also influenced their attitudes towards fertiliser application. Besides the use of mineral fertilisers, farmers employed other soil management strategies such as erosion control and the retention of crop residues. Among the farmers, key indicators of soil fertility were soil colour and crop performance with most farmers describing their soils as moderately fertile. Farmers preferred several traits including drought tolerance, high grain yield, earliness as well as varieties with lower fertiliser requirements. Farmers' constraints, perceptions and preferences may differ with location. Thus, a more extensive survey is required in other sorghum-growing regions in Ghana (Upper West and Northern Regions). This may reveal more insight into farmers' constraints and preferences which in turn will inform stakeholders and help prioritise breeding goals. The question also remains on whether on a wider scale, the behaviour of sorghum farmers' in northern Ghana, in terms of fertiliser input and cropping practices are influenced by their perceptions, adequate information on soil fertility or other processes. Studies to identify any linkage between farmers' perceptions, management practices and actual soil fertility are necessary to address soil fertility problems. In the meantime, access to

University of Ghana http://ugspace.ug.edu.gh

fertilisers and credit facilities must be improved to boost fertiliser use among smallholders. Better agricultural extension services are needed to educate farmers on the benefits of fertiliser-use and other soil fertility management methods.

In this study, induced mutagenesis was used as an efficient strategy for expanding genetic resources in sorghum. Several potentially-useful mutants were derived from the mutagenic treatment of BTx623. These include putative mutants for early flowering, late flowering, early senescence, brown mid-rib, multiple tillering, erect leaf architecture and bloomless characteristics. Characterisation of the putative mutants at more advanced generations and in diverse environments is required to eliminate any environmentally-influenced phenotypes and confirm the stability of the phenotypes observed at M_3. Upon confirmation, any desirable genotypes can be exploited for sorghum improvement either through selection or recombinant breeding. Further characterisation of the mutagenised population under different biotic and abiotic stress conditions may also be beneficial for identifying other useful traits which were not immediately visible at M_3. Given that the crop has been completely sequenced, it is also possible to isolate or confirm genes controlling identified traits in further genomic studies.

Further characterisation of the mutagenised population was carried out at M_6 as a strategy to identify and subsequently select P-use efficient genotypes. Significant variability was observed within the population for all measured traits in both low-P deficient and optimum-P environments. This suggests a fairly wide scope for further selections for P-use efficiency within this population. The P-use efficient genotypes identified in this study may be used to improve farmers' yields on marginal soils. However, multi-environment testing is necessary to fully confirm levels of tolerance to low-P stress as the data reported here (although from both pot and field environments) were obtained from single year trials. Following confirmation, any P-use efficient genotypes may

University of Ghana http://ugspace.ug.edu.gh

be advanced and used directly as mutant varieties or as parents in recombinant breeding programmes.

University of Ghana http://ugspace.ug.edu.gh

REFERENCES

Abane, J. A. (2015). The challenges of Millennium Development Goal 1 in Bongo District of the Upper East Region of Ghana. *Global Social Welfare*, 2 (1): 332–340.

Abdulai, A.L.I, Parzies, H., Kouressy, M., Vaksmann, M., Asch, F. and Brueck, H. (2012). Yield Stability of Photoperiod Sensitive Sorghum (*Sorghum bicolor* L. Moench) Accessions under Diverse Climatic Environments. *International Journal of Agricultural Research*, 7: 17-32.

Acquaah G. (2015). *Conventional Plant Breeding Principles and Techniques*. In: Al-Khayri J., Jain S., Johnson D. (eds) Advances in Plant Breeding Strategies: Breeding, Biotechnology and Molecular Tools. Springer, Cham.

Addai, I.K. and Alimiyawo, M. (2015). Graphical Determination of Leaf Area Index and its Relationship with Growth and Yield Parameters of *Sorghum* (*Sorghum bicolor* L. Moench) as Affected by Fertilizer Application. *Journal of Agronomy*, 14: 272-278.

Agropedia (2009). Phosphorus nutrition of sorghum. http://agropedia.iitk.ac.in/content/phosphorus-nutrition-sorghum. Accessed 12/11/2017.

Ahloowahlia, B.S., Maluszynski, M. and Nichterlein, K. (2004). Global impact of mutation-derived varieties. *Euphytica*, 135: 187-204.

Ai. P. H., Sun, S. B., Zhao, J. N., Fan, X. R., Xin, W. J., Guo, Q., *et al*. (2009). Two rice phosphate transporters, OsPht1; 2 and OsPht1; 6, have different functions and kinetic properties in uptake and translocation. *Plant Journal*, 57: 798–809.

Akinbile, L.A. (2003). Technology dissemination, agricultural productivity and poverty reduction in the rural sector of Nigeria. In: F Okunmadewa (Ed.): *Poverty Reduction and the Nigeria Agricultural Sector*, 58-78.

Alagarswamy, G. and Ritchie J.T. (2001). Phasic development in CERES Sorghum model. T. Hodges (Ed.), *Predicting Crop Phenology*, CRC Press, Boca Raton, FL: 143-152

Al-Hassan, R. and Jatoe**,** J.B.D. (2002). "Adoption and Impact of Improved Cereal Varieties in Ghana". Workshop on the Green Revolution in Asia and its Transferability to Africa. Organized by Foundation for Advanced Studies in International Development (FASID), from 8th – 10th December 2002. Tokyo, Japan

Alliance for a Green Revolution in Africa [AGRA] (2012). *Annual report of 2011*. Nairobi, Kenya.

Angelucci, F. (2013). Analysis of incentives and disincentives for sorghum in Ghana. *Technical notes series*, MAFAP, FAO, Rome.

University of Ghana http://ugspace.ug.edu.gh

AQUASTAT (2005). Irrigation in Africa in figures, AQUASTAT 2005 survey. Available at: http://www.fao.org/nr/water/aquastat/countries_regions/gha/GHA-CP_eng.pdf.

Arumuganathan, K., and Earle, E.D. (1991). Estimation of nuclear DNA content of plants by flow cytometry. *Plant Molecular Biology Reporter,* 9: 229–241.

Assefa, Y. and Staggenborg, S. (2011) Phenotypic changes in grain sorghum over the last five decades. *Journal of Agronomy and Crop Science*, 197: 249–257

Atokple, I.D.K. (2010). Sorghum and Millet Breeding in West Africa in Practice. http://www.afripro.org.uk/papers/Paper14Atokple.pdf. Accessed on 30th November, 2017

Atokple, IDK. (2012). Hybrid sorghum production. Presentation at the Bioscience for farming in Africa, Journalist training course, Accra, Ghana, September 19 – 22, 2012.

Axtell, J. D., Van Scoyoc, S. W., Christensen, P. J. and Ejeta, G. (1979). In: *Seed protein improvement in cereals and grain legumes* (Vienna: IAEA), 2: 35

Baba, S. U. (2017). Farmers' perceptions of Soil Degradation in Rural Kano, Northern Nigeria, *Resources and Environment*, 7: 8-12.

Bationo, A. and Mokwunye, A.U. (1991). Role of manures and crop residue in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. *Fertilizer Research*, 29: 117.

Bationo, A., Mokwunye U., Vlek, P.L.G., Koala, S. and Shapiro, B.I. (2003). *Soil fertility management for sustainable land use in the West African Sudano-Sahelian Zone*. In: *Soil fertility management in Africa*: *A regional perspective*. Academic Science Publishers. African Academy of Sciences, Nairobi, Kenya.

Bationo, A., Waswa, B., Kihara, J. and Kimetu, J. (2006). Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and opportunities. *Nutrient Cycling in Agroecosystems*, 76.

Bationo, A., Waswa, B., Abdou, A., Bado, B.V., Bonzi, M., Iwuafor, F., *et al*., (2012). *Overview of Long term experiments in Africa*. In: Bationo, Lessons Learned from Long Term Soil Fertility Management Experiments in Africa. Springer, Dordrecht, 1–26.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E. *et al*. (2012). *Knowing the African soils to improve fertilizer recommendations*. In: Kihara, J. et al. (eds.). Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer Dordrecht, 19-42

Bänziger, M., Bétran, F.J. and Lafitte, H.R. (1997). Efficiency of high-nitrogen environment for improving maize for low-nitrogen environment. *Crop Science,* 37:1103-1109

University of Ghana http://ugspace.ug.edu.gh

Banziger, M. and Cooper, M. (2001). Breeding for low-input conditions and consequences for participatory plant breeding: examples from tropical maize and wheat. *Euphytica*, 122: 503-519

Bayala, J., Bazié, H.R., Sanou, J. (2013). Competition and facilitation-related factors impacts on crop performance in an agroforestry parkland systems in Burkina Faso. *African Journal of Agricultural Research* 8 (43): 5303-5310.

Bentley, A., MacLennan, B., Calvo, J. and Dearolf, C.R. (2000). Targeted recovery of mutations in Drosophila. *Genetics* 156:1169–1173.

Berenji, J. and Dahlberg, J. (2004). Perspectives of sorghum in Europe. *Journal of agronomy and crop science*, 190 (5): 332 -338.

Benard, R., Dulle, F. and Ngalapa, H. (2014). Assessment of information needs of rice farmers in Tanzania; A case study of Kilombero District, Morogoro. *Philosophy and Practice*, 1071. http://unllib.unl.edu//LPP (Accessed 18 September 2015).

Bhargava, B. S.and Raghupathi, H. B. (1984). *Analysis of plant materials for macro and micro-nutrients.* In: H.L.S. Tandon (ed.), Methods of Analysis of Soils, Plants, Waters and Fertilizers. Fertilizer Development and Consultation Organization, 49-82.

Bhattacharya, A., Rice, N., Shapter, F. M., Norton, S. L. and Henry, R.J. (2011). *Sorghum and its wild crop relatives*. In Kole, C. (ed.) Wild Crop Relatives: Genomic and breeding. Resources Cereals, Springer, Heidelberg. 397-406.

Blum, A. (2005). Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? *Australian Journal of Agricultural Research*, 56:1159–1168.

Bolland, M. D. A. and Baker, M. J. (1988). High phosphorus concentrations in seed of wheat and annual medic are related to higher rates of dry matter production of seedlings and plants. *Australian Journal of Experimental Agriculture*, 28: 765–770

Borrell, A. K., Hammer, G. L.and Douglas, A. C. (2000). Does maintaining green leaf area in sorghum improve yield under drought? Leaf growth and senescence. *Crop Science*, 40:1026–1037.

Bouyoucos, G.H. (1951) A Recalibration of the Hydrometer for Making Mechanical Analysis of Soils. *Agronomy Journal*, 43: 434 - 438.

Bowers, J. E., Arias, M.A., Asher, R., Avise, J.A., Ball, R.T., Brewer, G.A. *et al*. (2005). Comparative physical mapping links conservation of microsynteny to chromosome structure and recombination in grasses. *Proceedings of the National Academy of Sciences,USA* 102(37):13206–13211.

University of Ghana http://ugspace.ug.edu.gh

Braimoh, K. and Vlek, P.L.G. (2004). The impact of land-cover change on soil properties in northern Ghana. *Land degradation and Development,* 15 (1): 65-74.

Brammer, H. (1962). *Soils*: In Agriculture and Land use in Ghana. J.B Wills (ed.), Oxford University Press London, Accra, New York. Pp 88-126.

Brar, D. S. and Jain, S.M. (1998). Somaclonal variation, mechanisms and applications in crop improvement. In: Somaclonal variation and induced mutations in crop improvement. Kluwer, Dordrecht. pp 15-38.

Bray, R. and Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59: 39–46.

Breseghello, F. and Coelho A. S. G. (2013). Traditional and modern plant breeding methods with examples in rice (*Oryza sativa* L.). *Journal of Agricultural and Food Chemistry*, 61: 8277–8286.

Broadley, M.R., White, P.J., Hammond, J.P., Zelko, I., Lux, A. (2007). Zinc in plants. *New Phytologist*, 173: 677–702.

Brundrett, M.C. (2009). Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. *Plant Soil,* 320: 37–77.

Buah, S.S.J., Kombiok, J.M. and Abatania, L.N. (2012). Grain sorghum response to NPK fertilizer in the Guinea savanna of Ghana. *Journal of Crop Improvement,* 26:101–115.

Buerkert, A., Bationo, A. and Piepho, H. P. (2001). Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. *Field Crops Research,* 72: 1–15.

Bumb, B.L., Johnson, M.E., Fuentes, P.A. (2011). IFPRI; Washington DC. Policy Options for Improving Regional Fertilizer Markets in West Africa. IFPRI Discussion Paper 01084: 73.

Buresh, R.J. and Smithson, P.C. (1997). *Building soil phosphorus capital in Africa*. In: Buresh at al. (Eds). Replenishing Soil Fertility in Africa. SSA Special Publication, 51. Madison, Wisconsin, USA.

Burow, G., Franks, C.D., Acosta-Martinez, V. and Xin, Z. (2008). Molecular mapping and characterization of BLMC, a locus for profuse wax (bloom) and enhanced cuticular features of Sorghum (Sorghum bicolor (L.) Moench.). Theoretical and applied genetics. 118. 423-31.

Burow, G., Xin, Z., Hayes, C., Burke, J. (2014). Characterization of a multi-seeded mutant of Sorghum for increasing grain yield. *Crop Science* 54: 2030–2037.

University of Ghana http://ugspace.ug.edu.gh

Burton, G.W. (1952). Quantitative inheritance in grasses. Proceedings of the 6th International Grasslands Congress Journal, 1:227 – 283.

Butchee, K., Arnall, D.B, Sutradhar, A., Godsey C., Zhang, H., and Penn, C. (2012). "Determining Critical Soil pH for Grain Sorghum Production," *International Journal of Agronomy*, 6:1 -6.

Cai, H. G., Mi, G. H., Chen, F. J., Zhang, X. Z., Gao, Q. (2010). Genotypic variation of leaf SPAD value, nitrogen and nitrate content in maize. *Acta Metallurgica Sinica*, 16 (4): 866 - 873.

Caldwell, D.G., McCallum, N., Shaw, P., Muehlbauer, G.J., Marshall, D.F. and Waugh, R. A (2004). Structured mutant population for forward and reverse genetics in barley *(Hordeum vulgare L.). The Plant Journal*, 40:143-150.

Camargo, C.E. De O., Felicio, J.C., Tulmann Neto, A. Ferreira Filho, A.W.P., Pettinelli Jr., A. and Castro, J.L. (1995). Wheat breeding: XXVIII. New genotypes obtained by selections in interspecific segregate population submitted to gamma irradiation. *Bragantia*, 54: 51-65.

Chambers, R. (1992c). *Rural appraisal: Rapid, relaxed and participatory*. IDS Discussion Paper 311. Brighton: IDS.

Chanterau, J., Trouche G., Rami, J. F., Deu M., Barro, C. Grivet, L. (2001). RFLP mapping of QTLs for photoperiod response in tropical sorghum. *Euphytica*, 120:183–194.

Chen, J., L. Xu, Y. Cai, and Xu. J. (2008). QTL mapping of phosphorus efficiency and relative biologic characteristics in maize (*Zea mays* L.) at two sites. *Plant Soil*, 313:251–266.

Chen, D., Wang, S., Xiong, B., Cao, B., & Deng, X. (2015). Carbon/Nitrogen Imbalance Associated with Drought-Induced Leaf Senescence in *Sorghum bicolor*. *PLoS One*, 10 (8).

Chianu, J.N., Chianu, J.N., Mairura, F. (2012). Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. *Agronomy for Sustainable Development*, 32:545–566.

Christiaensen, L., and Demery, L., and Kuhl, J. (2010). The (Evolving) Role of Agriculture in Poverty Reduction: An Empirical Perspective, WIDER Working Paper 2010/36.

Chung, K.-T., Wong, T.-Y., Huang, Y.-W., Lin, Y. (1998). Tannins and human health: a review. *Critical Review of Food Science and Nutrition*, 38: 421–464.

Ciarelli, D.M., Furlani, A.M.C., Dechen, A.R. and Lima, M. (1998). Genetic variation among maize genotypes for phosphorus-uptake and phosphorus-use efficiency in nutrient solution. *Journal of Plant Nutrition*, 21: 2219-2229.

University of Ghana http://ugspace.ug.edu.gh

Cisse, N. and Ejeta, G. (2003). Genetic variation and relationship among seedling vigor traits in sorghum. *Crop Science*, 43: 824-828.

Clayton, W.D., and Renvoize, S.A. (1986). Genera Graminum grasses of the world, Kew Bulletin Additional Series XIII, Royal Botanic. 338-345.

Condron, L.M, Turner, B.L., Cade-Menun, B.J. (2005). *Chemistry and dynamics of soil organic phosphorus.* In: Sims, J.T., Sharpley, A.N. (Eds.), Phosphorus: agriculture and the environment. ASA/CSSA/SSSA, Madison, Wisconsin. United States of America, 87-121.

Cordell, D., Drangert, J.O and White, S. (2009). The story of phosphorus: global food security and food for thought. *Global Environmental Change*, 19: 292-305

Cordell, D. and White, S. (2015). Tracking phosphorus security: indicators of phosphorus vulnerability in the global food system. *Food Security*, Springer, 7(2): 337-350**.**

Crawford, N.M and Forde, B.G. (2002). *Molecular and developmental biology of inorganic nitrogen nutrition.* The Arabidopsis Book: American society of plant biologists, 1.

Curt, M .D. Fernandez, J. and Martinez, M. (1995). Productivity and water use efficiency of sweet sorghum (Sorghum bicolor (L.) Moench) cv. "Keller"; in relation to water regime. *Biomass and Bioenergy*, 8 (6): 401- 409.

Daba, S. and Zewedie, E. (2001). Evaluation of the residual value of phosphorus fertilizer for sorghum (Sorghum bicolor L.) grown on a vertisol. *Bodenkultur*, 52:175-181.

Dahlberg, J., Berenji, J., Sikora, V. and Latkovic, D. (2011). Assessing sorghum (*Sorghum bicolor* (L) Moench) germplasm for new traits: food, fuels and unique uses. *Maydica*, 56 (1750): 85-92.

Deenanath, E. D., Iyuke, S., and Rumbold, K. (2012). The Bioethanol Industry in Sub-Saharan Africa: History, Challenges, and Prospects. *Journal of Biomedicine and Biotechnology*, 416-491.

De Lacerda, C.F., Cambraia, J., Oliva M.A., Ruiz, H.A. (2005). Changes in growth and in solute concentrations in sorghum leaves and roots during salt stress recovery. *Environmental and Experimental Botany*, 54: 69-76.

Dhillon, M. K., Sharma, H. C., Ram, S., Naresh, J. S. (2005). Mechanisms of resistance to shoot fly, *Atherigona soccata* in sorghum. *Euphytica* 144: 301–312.

Dillon, S.L., Frances, M., Shapter, R. J. H., Cordeiro, G., Izquierdo, L., Slade Lee, L. (2007). Domestication to Crop Improvement: Genetic Resources for *Sorghum* and S*accharum* (Andropogoneae). *Annals of Botany*, 100, (5): 975–989.

Diao, X., Cossar, F., Houssou, N., Kolavalli.S. (2014). Mechanization in Ghana: Emerging demand and the search for alternative supply models. *Food Policy*, 48: 168–181.

University of Ghana http://ugspace.ug.edu.gh

de Wet, J.M.J. and Huckabay, J.P. (1967). Origin of Sorghum bicolor. II. Distribution and Domestication. *Evolution,* 21: 787–802.

de Wet, J.M.J., (1978). Systematics and evolution of *Sorghum sect. bicolor* (Gramineae). *American Journal of Botany*, 65: 477–484.

de Wet, J., and Harlan, J. (1970). Apomixis, Polyploidy, and Speciation in Dichanthium. *Evolution, 24*(2): 270-277.

Diehl, L. (1992). *Smallholder Farming Systems in the Northern Region.* In: Acquaye DK (ed.). Improving Farming Systems in the Interior Savannah Zone of Ghana. Ghana: Nyankpala Agricultural Research Report (8) 2-13.

Devau, N., Le Cadre, E., Hinsinger, P, and Gérard F. (2010). A mechanistic model for understanding root-induced chemical changes controlling phosphorus availability. *Annals of Botany*, 105:1183–1198.

Dingkuhn, M., B. Singh, B. Clerget, J. Chantereau, and Sultan, B. (2006). Past, present and future criteria to breed crops for water-limited environments in West Africa. *Agriculture Water Management*, 80 (1–3), 241–261.

Doggett, H, (1965b). Disruptive selection in crop development. *Nature,* 206: 279-280.

Doggett, H. (1970). Recurrent selection in sorghum populations. *Heredity*, 28: 9-29

Doggett, H. (1988). *Sorghum*, 2nd Ed, Longman Scientific & Technical, Harlow, UK.

Doggett, H. (1988), Sorghum. *Tropical Agriculture Series*. 2nd ed. CTA, Wageningen, The Netherlands.

Dossou-Aminon, I., Yêyinou Loko, L., Adjatin, A., Ewedje, E.B.K., Dansi, A., Rakshit, S., et al. (2015). Genetic Divergence in Northern Benin Sorghum (*Sorghum bicolor* L. Moench) Landraces as Revealed by Agromorphological Traits and Selection of Candidate Genotypes. *The Scientific World Journal*, 6-10.

Doumbia, M.D., Hossner, L.R. and Onken, A.B. (1993). Variable sorghum growth in acid soils of sub-humid West Africa. *Arid Soil Research and Rehabilitation*, 7:335–346.

Doumbia, M.D., Sidibé, A., Bagayoko, A., Diarra, M.A., Bationo, A., Kablan, R.A., Yost, R.S., Hossner, L.R., Hons, F.M. (2003). Specific fertiliser recommendations: Calibration and validation of the phosphorus module of the NuMaSS model. African Crop Science Journal. 11: 17-26

University of Ghana http://ugspace.ug.edu.gh

Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F. (2001). Lecture notes on the major soils of the world. FAO World Soil Resources report 94: 334.

Druilhe, Z. and Barreiro - Hurle, J. (2012). Fertilizer subsidies in sub-Saharan Africa. ESA Working paper 12, Rome, FAO.

Duan, Y.H., Zhang, Y.L., Ye, L.T., Fan, X.R., Xu, G.H. and Shen, Q.R. (2007). Responses of rice cultivars with different nitrogen use efficiency to partial nitrate nutrition. *Annals of Botany*, 99:1153-1160.

Duvick, D.N. and Cassman, K.G. (1999). Post-Green Revolution Trends in Yield Potential of Temperate Maize in the North-Central United States. *Crop Science*, 39:1622-1630.

Eguavoen, I. (2013). Climate change and trajectories of blame in northern Ghana. *Anthropological Notebooks*, 19 (1): 5-24.

Elangovan, M., Jain S. K., Patel N. V. (2013). Characterization of sorghum germplasm collected from gujarat. *Indian Journal of Plant Genetic Resources*, 26 (1):42–46.

Elangovan, M., Kiran babu, P., Seetharama, N, Patil, J. V. (2014). Genetic Diversity and Heritability, characters Associated in Sweet Sorghum [*Sorghum bicolor* (L.) Moench]. *Sugar Technology*, 16:200–210.

El-Bassam, N. (2010). *Handbook of Bioenergy Crops*. A Complete Reference to Species, Development and Applications. Part II, 319- 333.

El-Din, A.A.T., Hessein, E.M., Ali, E.A. (2012). Path coefficient and correlation assessment of yield and yield associated traits in sorghum (*Sorghum bicolor* L. Moench). *American-Eurasian Journal of Agricultural and Environmental Science,* 12: 815–819.

El-Swaify, S.A, Pathak, P., Rego, T.J., Singh, S. (1985). Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *Advances in Soil Sciences*, 1: 1-64

Enu, P. and Attah-Obeng, P. (2013). Which Macroeconomic Factors Influence Agricultural Production in Ghana? *Academic Research International*, 4 (5): 333 – 346.

Environmental Protection Agency [EPA], (2003). Annual Report: Revised Draft, Environmental Protection Agency, Accra, Ghana.

Fairhurst, T. R., Lefroy, R. Mutert, E. and Batijes, N. (1999). The importance, distribution and causes of phosphorus deficiency as a constraint to crop production in the tropic. *Agroforestry Forum*, 9: 2-8, 1999.

University of Ghana http://ugspace.ug.edu.gh

Falconer, D. S., (1960a). *Introduction to Quantitative Genetics*. Oliver & Boyd, Edinburgh, London.

Food and Agriculture Organization of the United Nations [FAO] (1994). The state of Food and Agriculture. FAO Agriculture series (27). Available at: http://www.fao.org/docrep/t4450e/T4450E00.htm. Accessed on 14th October 2013.

Food and Agriculture Organization of the United Nations [FAO] (2009). Food security and agricultural mitigation in developing countries: Options for capturing synergies. Rome, Italy: Available at: http://www.fao.org/docrep/012/i1318e/i1318e00.pdf.

Food and Agriculture Organization of the United Nations Statistics [FAOSTAT] (2012). http://faostat.fao.org/site/575/default. Accessed on 2nd May 2014.

Food and Agriculture Organization of the United Nations [FAO] (2010). Sorghum. http://faostat.fao.org/site/567/default.aspx. Accessed on 10th December 2015.

Food and Agriculture Organization of the United Nations [FAO] (2013b). FAOSTAT Database. Rome: FAO.

Food and Agriculture Organization of the United Nations [FAO] (2014). The state of food and agriculture: Innovation in family farming. Rome: Food and Agriculture Organization of the United Nations

FAOSTAT (2015). http://www.fao.org/faostat/en/#data/QC. Accessed on 12th November 2014.

Feddermann, N., Finlay, R., Boller, T., Elfstrand, M. (2010). Functional diversity in arbuscular mycorrhizal—the role of gene expression, phosphorus nutrition and symbiotic efficiency. *Fungal Ecology*, 3: 1–8.

Fedorov, A. A. (1969). Chromosome Numbers of Flowering Plants. Leningrad: Academy of Sciences of the USSR. Komarov Botanical Institute. Goldblatt, P. (Ed). Index to plant chromosome numbers 1975 – 1978.

Fink, J. R., Inda, A. V., Bavaresco, J., Barron, V., Torrent, J. and Bayer, C. (2016). Phosphorus adsorption and desorption in undisturbed samples from subtropical soils under conventional tillage or no-tillage. *Journal of plant nutrition and soil science* 179 (2): 198-205.

Fosu-Mensah, B. Y., Vlek, P. L. G., and McCarthy, D. S. (2012). Farmers' perception and adaptation to climate change: A case study of Sekyedumase district in Ghana. *Environment, Development and Sustainability*, 14: 495-505.

Furihata, T., Suzuki, M., Sakurai, H. (1992) Kinetic characterization of two phosphate uptake systems with different affinities in suspension-cultured *Catharanthus roseus* protoplasts. *Plant Cell Physiology*, 33:1151–1157.

University of Ghana http://ugspace.ug.edu.gh

Gahoonia, T.S, Claassen, N. and Jungk, A. (1992). Mobilization of phosphate in different soils by ryegrass supplied with ammonium or nitrate. *Plant and Soil*, 140:241-248.

Gallais, A., Coque, M., Quilleré, I., Prioul, J.L. and Hirel, B. (2006). Modelling post-silking N-fluxes in maize using ^{15}N-labelling field experiments. *New Phytologist,* 172:696-707.

Gamuyao, R., Chin, J.H., Pariasca-Tanaka, J., Pesaresi, P., Catausan, S., Dalid, I. Slamet-Loedin, C. *et al*. (2012). The Protein Kinase *PSTOL1* from Traditional Rice Confers Tolerance of Phosphorus Deficiency. *Nature*, 488 (7412): 535-539.

Garber, E.D. (1950). Cytotaxonomic studies in the genus Sorghum. University of California Publications in *Botany*, 23: 283 – 362.

Gelli, M., Duo, Y., Konda, A. J., Zhang, C., Holding, D. and Dweikat, I. (2014). Identification of differentially expressed genes between sorghum genotypes with contrasting nitrogen stress tolerance by genome-wide transcriptional profiling. *BMC Genomics*, 15:179.

Gemenet, D. C, Leiser, W.L., Beggi, F., Herrmann, L. H., Vadez, V. Rattunde, H.F.W. *et al.* (2016). Overcoming phosphorus deficiency in West African Pearl Millet and Sorghum Production systems; Promising Options for crop improvement. *Frontiers in plant science*, 7:1389.

Ghana Statistical Service [GSS] (2013). Millennium Development Goals Report 2013. Ghana Statistical Service. Accra.

Govindaraj, M., Vetriventhan, M. & Srinivasan, M. (2015). Importance of Genetic Diversity Assessment in Crop Plants and Its Recent Advances: An Overview of Its Analytical Perspectives. *Genetics Research International*, 1-14.

Goode, D.L., Halbert, C. and Arendt, E.K. (2003). Optimization of mashing conditions when mashing with unmalted sorghum and commercial enzymes. *Journal of American Society of Brewing Chemist*, 61: 69-78.

Grant, C.A., D.N. Flaten, D.J. Tomasiewicz, and Sheppard. S.C. (2001). The importance of early season phosphorus nutrition. *Canadian Journal of Plant Science*, 81:211–224.

Gregory, D.I. and Bumb, B. L. (2006). Factors affecting Supply of Fertilizer in Sub Saharan Africa. Agriculture and Rural Development Discussion Paper 24 World Bank, Washington DC.

Grundon, N.l., Asher, C.l., and Edwards, D.G. (1986). *Symptoms of nutritional deficiencies and toxicities in grain sorghum cv. Texas 61 OSR*. ln: Foale, M.A. and HenzelL R.G. eds, Proceedings First Australian Sorghum Conference, February 1986, Gatton, Australia, 6.1-6.10.

Gunes, A., Inal, A., Alpaslan, M., and Cakmak, I. (2006). Genotypic variation in phosphorus efficiency between wheat cultivars grown under greenhouse and field conditions. *Soil Science and Plant Nutrition*, 52: 470-478

University of Ghana http://ugspace.ug.edu.gh

Guo, P., Baum, M., Grando, S., Ceccarelli, S., Bai, G., Li, R. *et al.* (2009). Differentially expressed genes between drought-tolerant and drought-sensitive barley genotypes in response to drought stress during the reproductive stage. *Journal of Experimental Botany,* 60:3531 – 3544

Gyasi, E. and Uitto, J. (1997). Environment, Biodiversity and Agricultural Change in West Africa; Perspectives from Ghana. United Nations University Press. Available at: http://www.unu.edu/unupress/unupbooks/80964e/80964E00.htm

Hammond, J.P., Broadley, M.R., White, P.J, King, G.J., Bowen, H.C., Hayden, R. *et al. (*2009). Shoot yield drives phosphorus use efficiency in *Brassica oleracea* and correlates with root architecture traits. *Journal of Experimental Botany*, 60*:* 1953–1968.

Hansen, J.C., Cade-Menun, B.J., Strawn, D.G. (2004) Phosphorus speciation in manure-amended alkaline soils. *Journal of Environmental Quality*, 33: 1521–1527.

Harlan, J. and De Wet, J. (1972)**.** A simplified classification of cultivated sorghum. *Crop Science,* 12(2):172-176.

Harlan, J.R. (1972). *A new classification of cultivated sorghum*. In: Sorghum in Seventies N.G.P. Rao and L.R. House (eds.). Oxford & IBH, New Delhi, India. 512-516.

Harrison, M. (2005) Signaling on the arbuscular mycorrhizal symbiosis. *Annual Reviews in Microbiology*, 59:19–42.

Hart, G.E., Schertz, K.F., Peng, Y. and Syed, N.H. (2001). Genetic mapping of *Sorghum bicolor* (L.) Moench QTLs that control variation in tillering and other morphological characters. *Theoretical Applied Genetics,* 103: 1232–1242.

Hash, C. T., Schaffert, R. E. and Peacock, J. M. (2002). Prospects for using conventional techniques and molecular biological tools to enhance performance of 'orphan' crop plants on soils low in available phosphorus. *Plant and soil*, 245: 135-146.

Henikoff, S. and Comai, L. (2003). Single-nucleotide mutations for plant functional genomics. *Annual Review of Plant Biology*, 54: 375-401.

Hernandez, M.A. and Torero, M.T. (2011). Fertilizer Market Situation. Market Structure, consumption and trade patterns, and pricing behavior. IFPRI Discussion Paper 1058. International Food Policy Research Institute.

Henao, J, and Baanante, C. (2006). Agricultural production and soil nutrient mining in Africa: Implication for resource conservation and policy development. IFDC Tech. Bull. International Fertilizer Development Center. Muscle Shoals, Al. USA.

Hinsinger, P. (1998). How do plant roots acquire mineral nutrients? Chemical processes involved in the rhizosphere. *Advance Agronomy*, 64: 225–265.

University of Ghana http://ugspace.ug.edu.gh

Hinsinger P. (2001). Bioavailability of soil Inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil*, 237: 173-195.

Hodge, A., Berta, G., Doussan, C., Merchan, F. and Crespi, M. (2009). Plant Root Growth, Architecture and Function. *Plant and Soil*, 321: 153-187.

Holford, I.C.R. (1997). Soil phosphorus: its measurements and its uptake by plants. *Australian Journal of Soil Research*, 35: 227-239.

Holford, I. C. R.; Hird, C.; Lawrie, R. (1997). Effects of animal effluents on the phosphorus sorption characteristics of soils. *Australian Journal of Soil Research*, 35: 365-373.

House, L.R., (1978). *A guide to Sorghum breeding*. International Crop Research Institute for Semi-Arid Tropics (ICRISAT), Patancheru, A.P., India.

House L.R. (1985). *A guide to sorghum breeding*, Second edition. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics: 165.

ICRISAT (2006). Nurturing the seeds of success in the semi-arid tropics. ICRISAT Annual Report 2006. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Hyderabad.

International Fertilizer Development Center [IFDC] (2006). Africa Fertilizer Summit Proceedings, Abuja, Nigeria June 9–13; IFDC, Florence, Alabama.

Issaka, Y. B., Antwi, M. and Tawia, G. (2016). Organic and non-organic farms in West Mamprusi district of Ghana. *Agriculture*, 6: 13.

International Fund for Agricultural Development [IFAD] (2010). Rural Poverty Report 2010: New Realities, New Challenges: New Opportunities for Tomorrow's Generation. Rome: Quintily.

Jenks, M. A., Joly, R. J., Peters, P. J., Rich, P. J., Axtell, J. D., Ashworth, E. A. (1994a). Chemically-induced cuticle mutation affecting epidermal conductance to water vapor and disease susceptibility in *Sorghum bicolor* (L.) Moench. *Plant Physiology*, 1051(1):1239–1245.

Jiao, Y., Burke, J., Chopra, R., Burow, G., Chen, J., Wang, B., Hayes, C., Emendack, Y., Ware, D. and Xin, Z. (2016) A sorghum mutant resource as an efficient platform for gene discovery in grasses. *Plant Cell*, 28 (7):1551–1562.

Jones, C. D., Cox, P.M., Essery, R.L.H., Roberts, D.L. and Woodage, M.J. (2003), Strong carbon cycle feedbacks in a climate model with interactive CO_2 and sulphate aerosols. *Geophysical Research Letter*, 30 (9):1479.

University of Ghana http://ugspace.ug.edu.gh

Jordan, W.R., McCrary, M. and Miller, F.R., (1979). Compensatory growth in the crown root system of sorghum. *Agronomy Journal*, 71: 803-806.

Kaeppler, S.M., Kaepller, H.F., Rhee, Y., (2000). Epigenetic aspects of somaclonal variation in plants. *Plant Molecular Biology*, 43: 179–18.

Kaizzi, C.K., Ssali, H., Nansamba, A., Vlek, P.L.G. (2007). *The potential benefits of Azolla, velvet bean (Mucuna pruriens) and N fertilizers in rice production under contrasting systems of eastern Uganda*. In: Bationo A, Kihara J, Kimetu J, Waswa B (eds) Advances in Integrated Soil Fertility Research in sub-Saharan Africa: Challenges and Opportunities. 423- 433.

Kaizzi, K.C., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza, W., Nansamba, A., *et al*. (2012). Sorghum response to fertilizer and nitrogen use efficiency in Uganda. *Agronomy Journal*. 104:83-90.

Kamara, A.Y., Kling, J.G., Menkir, A., Ibikunle, G. (2003). Agronomic performance of maize (Zea mays L.) breeding lines derived from a low nitrogen maize population. *Journal of Agricultural Science*, 141:221-230.

Kanchebe, E. (2010). Local Knowledge and Livelihood Sustainability under Environmental Change in Northern Ghana- PhD thesis. Center for Development Research, University of Bonn. Available from: http://hss.ulb.uni-bonn.de:90/2010/2336/2336.htm

Kang B. T. (1985). *Cropping systems and soil fertility management in the humid and sub-humid tropics with special reference to West Africa*. In: *Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa*, Mokwunye U., Vlek P. L. G., (eds) 83–94.

Katyal, J.C. and Das, S.K. (1993). *Fertiliser management in grain sorghum*. In: Tandon HLS (ed) Fertiliser Management in Food Crops: 61–78. Fertiliser Development and Consultation Organisation, New Delhi, India.

Kelly, V. (2006). Factors Affecting Demand for Fertilizer in Sub-Saharan Africa. Discussion Paper 23, Agriculture and Rural Development Department, the World Bank, Washington D.C.

Khorgade, P.W., Narkhede. M.N. and Raut, S.K. (1985). Genetic variability studies in chickpea (*Cicer arietinum* L.). *International Chickpea Newsletter*, 12-13.

Kidd, P.S. and Proctor, J. (2001). Why plants grow poorly on very acid soils: are ecologists missing the obvious? *Journal of Experimental Botany*, 52 (357): 791–799.

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

Kimaru-Muchai, S., Mucheru-Muna, M., Mugwe, J., Mugendi, D., Mairura, F., Tsobeng, A and Tchoundjue, Z. (2013). *Communication channels used in dissemination of soil fertility*

University of Ghana http://ugspace.ug.edu.gh

management practices in the central highlands of Kenya. In: Agro-Ecological Intensification of Agricultural Systems in the African Highlands. B. Vanlauwe, P. van Asten, G. Blomme (Eds.). 281-291.

Kimber, C.T. (2000*). Origins of domesticated sorghum and its early diffusion into India and China*. In 'Sorghum: Origin, History, Technology, and Production', C. Wayne Smith and R.A. Frederiksen (eds). 3-98.

Kiruki, S., Onek, L.A., Limo, M., (2006). Azide-based mutagenesis suppresses *Striga hermonthica* seed germination and parasitism on maize varieties. *African Journal of Biotechnology*, 5: 866-870.

Kisinyo, P.O., Gudu, S.O., Othieno, C.O., Okalebo, J.R., Opala, P.A., Maghanga, J.K., Agala et al. (2012).Effects of lime, phosphorus and rhizobia on Sesbania sesban performance in a Western Kenyan acid soil. *African Journal of Agricultural Research*, 7(18): 2800 -2809.

Klopfenstein, C.F and Hoseney, R.C. (1995). *Nutritional properties of sorghum and the millets*. In: D.A.V Dendy (Ed), sorghum and the millets: Chemistry and Technology", American Association of Cereal chemists Inc. St. Paul, 125-168.

Kodym, A. and Afza, R. (2003). *Physical and chemical mutagenesis*. In: Grotewold E (ed) Plant functional genomics: methods and protocols. Methods in Molecular Biology. 236: 189 – 203.

Koegel, S., Ait Lahmidi, N., Arnould, C., Chatagnier, O., Walder, F., Ineichen, K., Boller, T., Wipf, D., Wiekem, A. and Courty, P. E. (2013). The family of ammonium transporters (AMT) in Sorghum bicolor: two AMT members are induced locally, but not systemically in roots colonized by arbuscular mycorrhizal fungi. *New Phytologist*, 198 (3): 853-865.

Kombiok, J.M., Buah, J.S.S. and Sogbedji, J.M. (2012). *Enhancing soil fertility for cereal crop production through biological practices and the integration of organic and in-organic fertilisers in northern savanna zone of Ghana*. In: Soil Fertility. R. Issaka (ed). INTECH online publishers. 3-31.

Konate, M. (1984). *Climate of sorghum and millet cultivation zones of the semi-arid tropics regions of West Africa*. In: Agrometeorology of Sand Millet in the Semi-arid Tropics. M V K Sivakumar and S M Virmani (Eds) Proceedings of International Symposium ICRISAT Center, 15–20. November, 101–114. ICRISAT, Hyderabad, India.

Kondo, M., Pablico, P.P., Aragones, D.V., Agbisit, R., Morita, S., Courtois, B. (2003). Genotypic and environmental variations in root morphology in rice genotypes under upland field conditions. *Plant and Soil*, 255:189-200.

University of Ghana http://ugspace.ug.edu.gh

Kong, L., Dong, J. and Hart, G. E. (2000). Characteristics, linkage-map positions, and allelic differentiation of *Sorghum bicolor* (L.) Moench DNA simple-sequence repeats (SSRs). *Theoretical and Applied Genetics*, 101, (3): 438–448.

Kpongor, D. (2007). Spatially explicit modeling of sorghum (Sorghum bicolor L) production on complex terrain of a semi-arid region of Ghana using APSIM. PhD thesis. Ecology and Development Series 51.Center for Development Research (ZEF), University of Bonn. Bonn, Germany. 132.

Kpongor, D. S., Tabo, R., Bationo, A., Fosu, M. and Vlek, P. (2009). Simulating Sorghum Yield Response to Mineral Fertilizer in Semi-arid Northern Ghana. Paper from GLOWA-Volta Project and the CGIAR Challenge Program on Water and Food [online]. Available: www.ifwf2.org/addons/download.presentation. Date accessed18th July 2016.

Kudadjie, C.Y., Struik, P. C., Richards, P. and Offei, S. K. (2004). Assessing production constraints, management and use of sorghum diversity in northeast Ghana: a diagnostic study. *Net Journal of Agricultural Science,* 52(3 - 4): 371-391.

Kudadjie, E. (2006). Integrating science with farmer knowledge; sorghum diversity management in northern-east Ghana. PhD. Thesis, Wageningen University. 220.

Kudadjie-Freeman, C. and Dankyi-Boateng, S. (2012). Gender and cultural dimensions of sorghum seed management in northeast Ghana. *Global Journal of Biology, agriculture and health sciences*, 1(2): 4-9.

Kumar, A.A., Reddy,V.S., Sharma, H.C., Hash, C.T., Srinivasa Rao, P., Ramaiah, B. and Sanjana, R.P. (2011). Recent advances in sorghum genetic enhancement research at ICRISAT. *American Journal of Plant Sciences,* 2:589–600.

Kwabiah, A.B., Palm, C.A., Stoskopf, N.C. and Voroney, R.P. (2003). Response of soil microbial biomass dynamics to quality of plant materials with emphasis on P availability. *Soil Biology and Biochemistry,* 35: 207–216.

Larkin, P.J. and Scowcroft, W.R. (1981). Somaclonal variation: a novel source of variability from cell cultures for plant improvement. *Theoretical and Applied Genetics,* 60: 197–214.

Laube, W., Schraven, B. and M. Awo. M. (2012). Smallholder adaptation to climate change: dynamics and limits in Northern Ghana. *Climate change,* 111: 753-774.

Lazarides, M., Hacker, J.B. and Andrew, M.H. (1991). Taxonomy, cytology and ecology of indigenous Australian sorghums (*Sorghum* Moench: Andropogoneae: Poaceae), *Australian Systematic Botany*, 4: 591-635

Legwaila, G. M., Balole, T.V. and S. K. Karikari, (2003). Review of sweet sorghum: a potential cash and forage crop in Botswana. UNISWA *Journal of Agriculture*, 12: 5–14.

University of Ghana http://ugspace.ug.edu.gh

Leiser, W.L., Rattunde, H.F., Piepho, H.P. and Parzies, H.K. 2012a. Getting the most out of sorghum low-input field trials in West Africa using spatial adjustment. *Journal of Agronomy and Crop Science,* 198:349–359.

Leiser, W. L., Rattunde, H. F.W. Weltzien, E., and Haussmann, B.I.G. (2014). Phosphorus uptake and use efficiency of diverse West and Central African sorghum genotypes under field conditions in Mali. *Plant Soil,* 377:383–394.

Leiser, W.L., Rattunde, H.F.W., Piepho, H.P., Weltzien, E., Diallo, A., Tourè, A.O., Haussmann, B.I.G. (2015) Phosphorous efficiency and tolerance traits for selection of sorghum for performance in phosphorous-limited environments. *Crop Science,* 55:1152 – 1162.

Leiser, W. L., Olatoye, M. O., Rattunde, H. F. W., Weltzien, E., Neumann, G., Haussmann, B. I. G. (2016). No need to breed for enhanced colonization by arbuscular mycorrhizal fungi to improve low-P adaptation of West African sorghums. *Plant Soil,* 401 51–64. 10.

Liang, Q. (2009). "Preface," in Induced Plant Mutations in Genomics Era. Food and Agriculture Organization of the United States.1.

Liao, H., Rubio, G. and Yan, X., (2001) Effect of phosphorus availability on basal root shallowness in common bean. *Plant and Soil*, 232: 69–79.

Luz, V.K., Silveira, S.F.S., Fonseca, G.M., Groli, E.L., Figueiredo, R.G. et al. (2016). Identification of variability for agronomically important traits in rice mutant families. *Bragantia*, *75*(1): 41-50.

Lynch, J. P. (1995). Root architecture and plant productivity. *Plant Physiology*. 109: 7–13.

Lynch, J.P. and Ho, M.D. (2005). Rhizoeconomics: carbon costs of phosphorus acquisition. *Plant and Soil,* 269:45-56.

Lynch, J.P. (2007) Roots of the second green revolution. *Australian Journal of Botany*, 55:1–20.

Lynch, J.P. and Brown, K.M. (2008). *Root strategies for phosphorus acquisition*. In: The Ecophysiology of Plant-Phosphorus Interactions. P. J. White & J. P. Hammond (Eds). New York: Springer.

MacCarthy, D. S., Vlek, P. L. G. (2012). Impact of climate change on sorghum production under different nutrient and crop residue management in semi-arid region of Ghana: a modeling perspective. *African Crop Science Journal,* 20 (2): 275-291

MacDonald, G.K., Bennett, E.M., Potter, P.A. and Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences, USA,* 108: 3086-3091.

University of Ghana http://ugspace.ug.edu.gh

Maerere, A.P, Kimbi, G.G. and Nonga, D.L.M. (2001).Comparative effectiveness of animal manures on soil chemical properties, yield and root growth of amaranthus (*Amaranthus cruentus* L.). *African Journal of Science and Technology*, 1 (4): 14-21.

Magalhaes, J.V., Liu, J., Guimarães, C.T., Lana, U.G.P., Alves, V.M.C. Wang, Y.H et *al.* (2007). A gene in the multidrug and toxic compound extrusion (MATE) family confers aluminum tolerance in sorghum. *Nature Genetics*, 39:1156–1161.

Mairura, F.S., Mugendi, D.N., Mwanje, J.I., Ramisch, J.J., Mbugua, P.K., Chianu, J.N. (2007). Integrating scientific and farmers' evaluation of soil quality indicators in Central Kenya. *Geoderma,* 139:134–143.

Maiti, R. K., Ramaiah, K. V., Bisen, S. S., Chidley, V. L. (1984). A comparative study of the haustorial development of *Striga asiatica* (L.) kuntze on sorghum cultivars. *Annals of Botany*, 54: 447–457.

Manske, G.G.B., Ortiz-Monasterio, J.I., van Ginkel, R.M. *et al*. (2002). Phosphorus use efficiency in tall, semi-dwarf and dwarf near isogenic lines of spring wheat. *Euphytica,* 125:113–119.

Manu, A., A. Bationo, and Geiger. S.C. (1991). Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. *Soil Sciences*, 152:315–320.

Mapfumo, P. and Giller, K.E. (2001). Soil fertility management strategies and practices by smallholder farmers in semi-arid areas of Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) with permission from the Food and Agricultural Organization (FAO), Bulawayo, Zimbabwe and Rome, Italy.

Marenya, P., Barrett, C.B. and Gulick. T. (2008). "Farmers Perceptions of Soil Fertility and Fertilizer Yield Response in Kenya." SSRN Scholarly Paper ID 1845546, Social Science Research Network, Rochester, NY.

Marschner, H. (1995) *Mineral Nutrition of Higher Plants*, Second edition. London: Academic Press.

Maqbool, S.B., Devi, P. and Sticklen, M.B. (2001). Biotechnology- Genetic Improvement of Sorghum (Sorghum bicolor (L.). *In Vitro Cellular and Developmental Biology- Plant*, 37:504-515.

Melese A., Gebrekidan, H., Yli-Halla M. and Yitaferu, B. (2015). Phosphorus Status, Inorganic Phosphorus Forms, and Other Physicochemical Properties of Acid Soils of Farta District, Northwestern Highlands of Ethiopia. *Applied and Environmental Soil Science*, 1-11.

Mehlich, A. (1984). Mehlich three soil test extractant: A modification of the Mehlich two extractant. *Communications in Soil Science and Plant Analysis*, 15:1409 -1416.

University of Ghana http://ugspace.ug.edu.gh

Menezes, C.B., Carvalho, J., de Silva, G.A., Assis, L., Bernardino, K., Costa, S., Vander, F., Tardin, F.D. and Schaffert, R.E. (2014). Combining ability of grain sorghum lines selected for Aluminum tolerance. *Crop Breeding and Applied Biotechnology*, 14 **(**1): 42-48.

Menz, M.A., Klein, R.R., Mullet, J.E., Obert, J.A., Unruh, N.C. and Klein, P.E. (2002). A high-density genetic map of *Sorghum bicolor* (L.) Moench based on 2926 AFLP, RFLP and SSR markers. *Plant Molecular Biology*, 48(5–6)**:**483–499.

Millar, D., Abazaami, J. and Bonye, S. (2007). Women, land and agricultural productivity: a study into community level constraints to land availability for women in Kalbeo and Gowrie Kunkwa. Centre for Cosmovision and Indigenous Knowledge (CECIK).

Miller, F.R. (1976). Release of A/BT×623. TAES Form 97-72. Report of Technical Committee on Seed Release and Increase. Texas Agriculture Experimental Station, College Station, TX.

Ministry of Food and Agriculture (MoFA). (2009). *Food and Agriculture Sector Development Policy (FASDEP II). Accra*. In: West African Agriculture and Climate Change: A Comprehensive Analysis. Jalloh, A., Nelson, G. C., Thomas, T. S., Zougmoré, R. and Roy-Macauley, H. (Eds), IFPRI. Washington, DC. Accesed from http://www.ifpri.org/sites/default/files/publications/rr178.pdf

Ministry of Food and Agriculture [MOFA] Ghana (2015). Talensi-Nabdam District in the Upper East. http://MoFA.gov.gh/site/?page id=1658

Missihoun, A.A., Agbangla, C., Adoukonou-Sagbadja, H., Ahanhanzo, C., Vodouhè, R. (2012a). Gestion traditionnelle et statut des ressources génétiques du sorgho (*Sorghum bicolor* L. Moench) au Nord-Ouest du Bénin. *International Journal of Biological and Chemical Science* 6(3):1003-1018.

Mizuno, H., H. Kawahigashi, J. Ogata, H. Minami, H. Kanamori, H. Nakagawa *et al*. (2013). Genomic inversion caused by gamma irradiation contributes to downregulation of a WBC11 homolog in bloomless sorghum. *Theoretical and Applied Genetics*, 126:1513–1520.

Mofokeng, A. M., Hussein, A. S. and Laing, M.D. (2017) Agro-morphological diversity of South African sorghum genotypes assessed through quantitative and qualitative phenotypic traits, *South African Journal of Plant and Soil*, 34: (5) 361-370.

Moges, W. and Holden, N.M. (2007). Farmers' perceptions of soil erosion and soil fertility loss in southern Ethiopia. *Land Degradation and Development*, 18(5):543-554.

Mokhema, T. (2013). South Africa biofuels seen raising sorghum output fivefold. www.https://advancedbiofuelsusa.info/south-africa-biofuels-seen-raising-sorghum-output-fivefold/. Accessed on 18th September 2016.

University of Ghana http://ugspace.ug.edu.gh

Moll, R.H, Kamprath, E.J and Jackson, W.A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. *Agronomy Journal*, 74 (3):562–564.

Molla, M., Chowdhury, A., Islam, A., and Hoque, S. (1984). Microbial mineralization of organic phosphate in soil. *Plant and Soil, 78*(3):393-399.

Murphy, J. and Riley, J.P. (1962). A Modified Single Solution Method for the Determination of Phosphate in Natural Waters. *Analytica Chimica Acta*, 27:31-36.

Mwangi, T.J., Ngeny, J.M., Wekesa, F., Mulati, J. (2002). *Acidic soil amendment for maize production in Uasin Gishu District, North Rift Kenya*. In: Gachene et al. (Eds), Participatory technology development by small holders in Kenya. Proceedings of the 2nd scientific conference of the soil management and legume research network projects. KARI, Nairobi, Kenya.

Nandwa, S. A, Bationo, A, Obanyi, S. N., Rao, I. M., Sanginga, N., Vanlauwe, B. (2011). Inter and intra-specific variation of legumes and mechanisms to access and adapt to less available soil phosphorus and rock phosphate. In: A. Bationo *et al.* (eds.). Fighting poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management,pp. 47-66.

Narayanan, S., Aiken, R.M., Vara, P.V., Zhanguo Xin, P., Paul, G., and Yu, J. (2014). A Simple Quantitative Model to Predict Leaf Area Index in Sorghum. *Agronomy Journal- Crop Ecology and Physiology*, 6, (1): 219 -226.

Ncube, B., Twomlow, S.J., Van Wijk, M.T., Dimes, J.P., Giller, K.E. (2007). Productivity and residual benefits of grain legumes to sorghum under semi-arid condition in south western Zimbabwe. *Plant Soil*, 229:1-15.

Ndamani, F. and Watanabe, T. (2015). Farmers' Perceptions about Adaptation Practices to Climate Change and Barriers to Adaptation: A Micro-Level Study in Ghana. *Water*, *7*:4593-4604.

Nekesa, A.O., Okalebo, J.R., Othieno, C.O., Thuita, M.N., Kipsat, M., Bationo, A., Sanginga, N., Kimettu, J., Vanlauwe, B. (2005). The potential of minjingu phosphate rock from Tanzania as a liming material: effect on maize and bean intercrop on acid soils of western Kenya. African Crop Science conference proceedings, 7: 1121-1128.

Nin-Pratt, A., McBride, L. (2014). Green Revolution in West Africa: Is increasing population density triggering an Asian-style agricultural intensification in Ghana? Food Policy.

Nkegbe, P.K. and Shankar, B. (2014). Adoption intensity of soil and water conservation practices by smallholders: evidence from northern Ghana. *Bio-based and Applied Economics*, 3 (2): 159-174.

Nyanteng, V. K. and Asuming-Brempong, S. (2003). The role of Agriculture in Food security in Ghana. Roles of Agriculture Project International Conference. 20-22 October, Rome, Italy.

University of Ghana http://ugspace.ug.edu.gh

Nziguheba, G. (2007). *Overcoming phosphorus deficiency in soils of Eastern Africa: recent advances and challenges*. In: Bationo A, Waswa B, Kihara J, Kimetu J (eds). Advances in integrated soil fertility management in Sub - Saharan Africa: Challenges and opportunities, Springer, 149-160.

Obura. P.A. (2008). Effects of soil properties on bioavailability of aluminium and phosphorus in selected Kenyan and Brazilian soils. Ph. D. Thesis, Purdue University, USA.

Ochieng, L., Mathenge, P. and Muasya, R. (2011). A survey of on-farm seed production practices of sorghum (Sorghum bicolor L. Moench) in Bomet District of Kenya. *African Journal of Food, Agriculture, Nutrition and Development,* 11(5): 270–276.

Odedina, J.N., Odedina, S.A. and Ojeniyi, S.O. (2011). Effect of types of manure on growth and yield of cassava (*Manihot esculenta*, Crantz). *Researcher*, 3 (5): 1 –8.

Ohene-Yankyera, K. (2004). Determinants of Farm Size in Land-Abundant Agrarian Communities of Northern Ghana. *Journal of Science and Technology*, 24 (2): 45-53.

Oliveira, A.B., Alencar, N.L.M., Prisco, J.T., and Gomes-Filho, E. (2011). Accumulation of organic and inorganic solutes in NaCl-stressed sorghum seedlings from aged and primed seeds. *Scientia Agricola*, 68 (6): 632-637.

Omondi, E. G. O., Makobe, M.N., Matasyoh, L.G. and Onyango, C.A. (2013). Genetic variability of tissue cultured Sorghum bicolor (L) Moench as revealed by morphological traits and simple sequence repeats (SSR) markers. *African Journal of Biotechnology*, 12(1): 1-7.

Omotayo, O. E. and Chukwuka, K.S. (2009). Soil fertility restoration techniques in sub-Saharan Africa using organic resources. *African Journal of Agricultural Research*, 4 (3): 144-150.

Oria, M.P., Hamaker,B.R., Axtell, J.D., Huang, C.P. (2000). A highly digestible sorghum mutant cultivar exhibits a unique folded structure of endosperm protein bodies. *Proceedings of the National Academy of Sciences, USA*, 97: 5065-5070.

Osarfo, D., Senadza, B. and Nketiah-Amponsah, E. (2016).The Impact of Nonfarm Activities on Rural Farm Household Income and Food Security in the Upper East and Upper West Regions of Ghana . *Theoretical Economics Letters*, 6: 388-400.

Ozturk, L., Eker, S., Torun, B. and Cakmak, I. (2005). Variation in phosphorus efficiency among 73 bread and durum wheat genotypes grown in a phosphorus-deficient calcareous soil. *Plant Soil*, 269: 69– 80.

Owusu-Bennoah, E. and Acquaye, D.K. (1996). Greenhouse evaluation of agronomic potential of different sources of phosphate fertilizer in a typical concretionary soil of Northern Ghana. *Fertility Research*, 44:1091–106.

Parentoni, S.N. and Souza, C.L. Jr (2008) Phosphorus acquisition and internal utilization efficiency in tropical maize genotypes. *Pesquisa Agropecuária Brasileira*, 43:893–901.

University of Ghana http://ugspace.ug.edu.gh

Parentoni, S., C. de Souza, Jr., V. de Carvalho Alves, E. Gama, A. Coelho, A. de Oliveira, P. *et al*. (2010). Inheritance and breeding strategies for phosphorus efficiency in tropical maize (*Zea mays* L.). *Maydica,* 55:1–15.

Parry, M. A. J., Madgwick, P. J., Bayon, C., Tearall, K., Hernandez-Lopez, A., Baudo, M. *et al*. (2009). Mutation discovery for crop improvement. *Journal of Experimental Botany*, 60(10): 2817- 2825.

Paterson, A.H., Bowers, J.E., Chapman, B.A. (2004). Ancient polyploidization predating divergence of the cereals, and its consequences for comparative genomics. *Proceeding of the National Academy of Science, USA,* 101: 9903–9908.

Paterson, A.H., Bowers, J.E. and Bruggmann, R. (2009). The Sorghum bicolor genome and the diversification of grasses. *Nature, 457:551-556.*

Parentoni, S.N., and C. Lopes de Souza, Jr. (2008). Phosphorus acquisition and internal utilization efficiency in tropical maize genotypes. *Pesquisa Agropecuária Brasileira*, 43:893–901.

Peters, P.J., Jenks, M.A., Rich,P.J. Axtell, J.D. and Ejeta. G. (2009). Mutagenesis, selection, and allelic analysis of epicuticular wax mutants in sorghum. *Crop Science*, 49:1250–1258.

Peterson DG, Schulze SR, Sciara EB, Lee SA, Bowers JE, Nagel ANJ, Tibbitts DC *et al*. (2002) Integration of Cot analysis, DNA cloning, and high-throughput sequencing facilitates genome characterization and gene discovery. *Genome Research*, 12: 795–807.

Phillips, S.L. and Wolfe, M.S. (2005). Centenary Review. Evolutionary plant breeding for low input systems. *Journal of Agricultural Science*, 143: 245-254.

Prasad, P.V.V., K.J. Boote, and L.H. Allen, Jr. (2006a). Adverse high temperature effects on pollen viability, seed-set, seed yield, and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agricultural and Forest Meteorology*, 139:237–251.

Prasad, P.V.V. and Staggenborg, S.A. (2009). *Growth and production of sorghum and millets. In soils, plant growth and crop production*. In: Encyclopedia of life Support Systems, Eolss Publishers, Oxford, UK. http:// www.eolss.net.

Quaye, W. (2008). Food security situation in northern Ghana, coping strategies, and related constraints. *African Journal of Agricultural Research,* 3 (5): 334-342.

Quijano-Guerta, C., Kirk, G.J.D., Portugal, A.M., Bartolome, V.I. and McLaren, G.C. (2002) Tolerance of rice germplasm to zinc deficiency. *Field Crop Research*, 76:123–130.

Quinby, J.R. (1975). The genetics of sorghum improvement. *Journal of Heredity*, 66:56 – 62.

University of Ghana http://ugspace.ug.edu.gh

Rakshit S., Gomashe S. S., Ganapathy K. N., et al. (2012). Morphological and molecular diversity reveal wide variability among sorghum Maldandi landraces from India. *Journal of Plant Biochemistry and Biotechnology*, 21(2):145–156.

Rakszegi, M., Kisgyörgy, B. N., Tearall, K., Shewry, P. R., Láng, L., Phillips, A., *et al*. (2010). Diversity of agronomic and morphological traits in a mutant population of bread wheat studied in the health grain program. *Euphytica*, 174, 409–421.

Rai, S., Kaur, A., and Singh, B. (2014). Quality characteristics of gluten free cookies prepared from different flour combinations. *Journal of Food Science and Technology*, 51(4):785–789.

Rajasekher, R.A., Ravinder R.V, Parthasarathy R.P., Gurava R.K., Belum V.S Reddy (2005). Performance of Layers on Sorghum-Based Poultry Feed Rations. International Sorghum and Millets Newsletter, ICRISAT, Patancheru, India, 46: 75-78.

Raju, P. S., Clark, R. B., Ellis, J. R., Duncan, R. R. and Maranville, J. W. (1990). Benefit and Cost Analysis and Phosphorus in Mycorrhizal Fungi Colonizations with Sorghum (*Sorghum bicolor*) Genotypes Grown at Varied Phosphorus Levels. *Plant Soil*, 124: 199–204.

Rao, I. M. (2001). *Role of physiology in improving crop adaptation to abiotic stresses in the tropics: The case of common bean and tropical forages*. In: Handbook of Plant and Crop Physiology. M. Pessarakli (Ed), 583–613. New York: Marcel Dekker.

Reddy, B.B.S., Ramesh, S., Reddy, P.S. (2006). Sorghum genetic resources, cytogenetics and improvement. In: Singh RJ, Jauhar PP, editors. Cereals. Vol. 2. Boca Raton, FL: CRC Taylor and Francis, pp. 309–363. *Genetic resources, chromosome engineering, and crop improvement.*

Reddy B.VS, Sharma, H.C., Thakur, R.P., Ramesh, S., Rattunde, F. and Mgonja, M. (2006) Sorghum hybrid parents research at ICRISAT: retrospect and prospects. *SAT e-journal* 2(1):1–24.

Reddy, K.R. and DeLaune, R.D. (2008). Biogeochemistry of Wetlands: Science and Applications. CRC press. 335-345.

Ribaut, J.M. and Poland, D. (2000). Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-limited Environments. A strategic planning workshop held at CIMMYT, El Batan, Mexico, 21–25 June 1999. International Maize and Wheat Improvement Center (CIMMYT).Mexico, DF, Mexico.

Richardson, A. E. (1994). *Soil microorganisms and phosphorus availability*. In: *Soil Biota Management in Sustainable Farming Systems*, Pankhurst C. E., Doubeand B. M. Gupta V. V. S. (Eds) (Melbourne, VIC: CSIRO Publishing): 50–62.

University of Ghana http://ugspace.ug.edu.gh

Risse, L.M., Cabrera, M.L., Franzluebbers, A.J., Gaskin, J.W., Gilley, J.E., Killorn, R., Radcliffe, D.E., Tollner, W. E., Zhang, H. (2006). Land application of manure for beneficial reuse. *Biological Systems Engineering*: Papers and Publications. Paper 65.

Riyazaddin, M., Ashok Kumar, A., Rajendra Sudhakar, M., Ramaiah, B., Kavi Kishor, B. Polavarapu, H. C. S (2016). Inheritance of resistance to Sorghum Shoot Fly, *Atherigona soccata* in sorghum, *Sorghum bicolor* (L.) Moench. *Frontiers in Plant Sciences*, 7: 543.

Rose T. J., Rengel Z., Ma Q., Bowden J. W. (2008). Post-flowering supply of P, but not K, is required for maximum canola seed yields. *European Journal of Agronomy*, 28: 371–379.

Rose, T.J. and Wissuwa, M. (2012). Rethinking internal phosphorus utilization efficiency. *Advances in agronomy*, Elsevier: 85–217.

Rose, T. J., Liu, L., & Wissuwa, M. (2013). Improving phosphorus efficiency in cereal crops: Is breeding for reduced grain phosphorus concentration part of the solution? *Frontiers in Plant Science*, *4*; 444.

Roy, P. K. Niyogi, K. Sengupta, D. N. Ghoosh, B. (2005). Spermidine treatment to rice seedlings recovers salinity stress-induced damage of plasma membrane and PM-bound H-ATPase in salt-tolerant and salt-sensitive rice cultivars. *Plant Science*, 168 (3): 583-591.

RUDEMA (Rural Development Management (2006). National Strategic Plan for Sorghum Development in Ghana. Final Report. 3-16

Rware, H., Wairegi, L., Oduor, G., Macharia, M., Romney, D., Tarfa, B.D. *et al*. (2014). Assessing the Potential to Change Stakeholders Knowledge and Practices on Fertilizer Recommendations in Africa. *Agricultural Science*, 5(14):1384.

Saballos, A., Vermerris, W., Rivera, L., Ejeta, G. (2008). Allelic association, chemical characterization and saccharification properties of *brown midrib* mutants of sorghum (*Sorghum bicolor* (L.) Moench). *Bioenergy Research*, 1: 193–204.

Sahrawat, K.L., T.J. Rego, J.R. Burford, M.H. Rahman, J.K. Rao, and Adam, A. (1995). Response of sorghum to fertilizer phosphorus and its residual value in a Vertisol. *Fertility Research*, 41:41–47.

Sahrawat, K.L, Mulbah, C.K., Diatta, S., DeLaune, R.D., Patrick Jr. W.H., Singh B.N., Jones M.P. (1996). The role of tolerant genotypes and plant nutrients in the management of iron toxicity in lowland rice. *Journal of Agricultural Science, Cambridge*, 126:143-149.

Samake, O., Smaling, E.M.A., Kropff, M.J., Stomph, T. J. and Kodio, A. (2005). Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. *Agriculture, Ecosystems and Environment*, 109 (4), 335- 345.

University of Ghana http://ugspace.ug.edu.gh

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.

SARI (1995). Savanna Agricultural Research Institute (SARI) annual Report (1995), Nyakpala, Ghana. 133.

Sattari, S.Z., Bouwman, A.F., Giller, K.E. and Van Ittersum, M.K. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proceedings of the National Academy of Sciences*, USA, 109: 6348-6353.

Sattler, S.E., Saballos, A., Xin, Z., Funnell-Harris, D.L., Vermerris, W., Pedersen, J.F. (2014). Characterization of novel Sorghum brown midrib mutants from an EMS-mutagenized population. *G3 (Bethesda)*, 4: 2115–2124

Schachtman, D.P., Reid, R.J., Ayling, S.M. (1998). Phosphorus uptake by plants: from soil to cell. *Plant Physiology*, 116:447–453.

Schaefer, C. E. G. R., Fabris, J. D. and Ker, J. C. (2008). Minerals in the clay fraction of Brazilian Latosols (Oxisols): a review. *Clay Minerals*, 43 (1): 137-154.

Schaffert, R.E., Alves, V.M.C., Pitta, G.V.E., Bahia, A.F.C. and Santos, F.G. (2001). Mechanisms of phosphorus efficiency in maze. In: Plant nutrition, food security and sustainability of agroecosystems through basic and applied research. WJ. Horst et al. (Eds.) Plant Nutrition-Food Security and sustainability of Agro-ecosystems, 72-73.

Schnell, J., Steele, M., Bean, J., Neuspiel, M., Girard, C. and Dormann, N. (2015). A comparative analysis of insertional effects in genetically engineered plants: Considerations for pre-market assessments. *Transgenic Research*, 24:1–17.

Schoonover, J. E. and Crim, J. F. (2015). An Introduction to Soil Concepts and the Role of Soils in Watershed Management. *Journal of Contemporary Water Research & Education*, 154(1):21–47.

Shen J. B., Yuan L. X., Zhang J. L., Li H. G., Bai Z. H., Chen X. P., *et al.* (2011). Phosphorus dynamics: from soil to plant. *Plant Physiology*, 156: 997–1005.

Shepherd, K.D., and Soule M.J. (1998). Soil fertility management in West Kenya; a dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. *Agricultural Ecosystems and Environment* 71, 131-145.

Shin H, Shin HS, Dewbre GR, Harrison MJ. (2004) Phosphate transport in Arabidopsis: Pht1;1 and Pht1;4 play a major role in phosphate acquisition from both low- and high-phosphate environments. *Plant Journal*, 39: 629–642

University of Ghana http://ugspace.ug.edu.gh

Shoemaker, C.E. and D.I. Bransby. (2010). The role of sorghum as a bioenergy feedstock. In: R. Braun, D. Karlen, and D. Johnson, editors, Sustainable alternative fuel feedstock opportunities, challenges and roadmaps for six U.S. regions, Proceedings of the Sustainable Feedstocks for Advance Biofuels Workshop, Atlanta, GA. 28–30 September. Soil and Water Conservation Society, Ankeny, 149–159.

Sikora, P., Chawade, A., Larsson, M., Olsson, J. and Olsson, O. (2011). Mutagenesis as a Tool in Plant Genetics, Functional Genomics, and Breeding. *International Journal of Plant Genomics*, 1-13.

Sinclair, T.R. (1998). Historical changes in harvest index crop nitrogen accumulation. *Crop Science*, 38:638-643.

Singh, R. J. and Jauhar, P. (2006). Genetic Resources, Chromosome. *Engineering and Crop Improvement*, Volume 2 Cereals. CRC Press, New York.

Smaling, E.M.A., (1993). *An ecological framework for integrated nutrient management with special reference to Kenya*. Ph.D. thesis, Wageningen Agricultural University, Wageningen.

Smalberger, S. A., Singh, U., Chien, S. H., Henao, J., and Wilkens, P. W. (2006). Development and validation of a phosphate rock decision support system. *Agronomy Journal*, 98: 471–483.

Smaling, E.M.A, Nandwa, S.M. and Janssen, B.H. (1997). Soil fertility is at stake. In: Buresh RJ, Sanchez PA & Calhoun F (Eds). *Replenishing soil fertility in Africa.* Special publication No. 51 Madison, Wisconsin: American Society of Agronomy and Soil Science society of America. 47-61.

Smith, C.W. and Frederiksen, R.A. (2000). Sorghum: origin, history, technology, and production, New York, NY John Wiley and Sons, 824.

Snowden, J.D. (1935). A classification of cultivated sorghum. *Kew Bulletin*, 5:221 – 255.

Sommer, R., Bossio, D., Desta, L., Dimes, J., Kihara, J., Koala, S., Winowiecki, L. (2013). Profitable and Sustainable Nutrient Management Systems for East and Southern African Smallholder Farming Systems-Challenges and Opportunities: A synthesis of the Eastern and Southern Africa situation in terms of past experiences, present and future opportunities in promoting nutrient use in Africa. Cali, Columbia, CIAT. Queensland, Australia: The University of Queensland, Queensland Alliance for Agriculture and Food Innovation (QAAFI), 91.

Sree Ramulu, K. (1970a). Induced systematic mutations in sorghum. *Mutation Research-Fundamental and Molecular Mechanism of Mutagen*, 10:77–80.

University of Ghana http://ugspace.ug.edu.gh

Srinivasa Rao, P., Kumar, C.G., Malapaka, J., Kamal, A. and Reddy, B. V. S. (2012). Feasibility of Sustaining Sugars in Sweet Sorghum Stalks during Post-Harvest Stage by Exploring Cultivars and Chemicals: A Desk Study. *Sugar Tech*, 14 (1): 21-25.

Su J., Xiao Y., Li M., Liu Q., Li B., Tong Y., et al. (2006). Mapping QTLs for phosphorus-deficiency tolerance at wheat seedling stage. Plant Soil 281, 25–36.

Su, Y J., Qin, Y. T., Zhang, S. L., Qin, G. W., Xu, G. J., Lu, R. Q., Mei, Z. J. (2012). Effects of planting density on growth and yield of summer maize Xundan 28. *Acta Agriculture Jiangxi*, 24 (6): 49- 53.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M. *et al*. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*, 8, (1).

Suzuki, T., Eiguchi, M., Kumamaru, T., Satoh, H., Matsusaka, H., Moriguchi, K. *et al*. (2008). MNU-induced mutant pools and high performance TILLING enable finding of any gene mutation in rice. *Molecular Genetics and Genomics, 279:*213-223.

Sweeney, D. W., Moyer, J. L., Jardine, D. J. and Whitney, D. A. (2011). Nitrogen, phosphorus and potassium effects on grain sorghum production and stalk rot following alfalfa and birdsfoot trefoil, *Journal of Plant Nutrition*, 34, (9):1330-1340.

Talebi, A. B., Talebi, A. B. and Shahrokhifar, B. (2012). Ethyl methane sulphonate (EMS) induced mutagenesis in malaysian rice (cv. MR219) for lethal dose determination. *American Journal of Plant Sciences*, 3:1661-1665.

Tan K., Keltjens, W.G. and Findenegg, G.R. (1991). Role of magnesium in combination with liming in alleviating acid-soil stress in the aluminium-sensitive sorghum genotype CV323. *Plant and Soil*, 136: 65-71.

Tan, W., Bogre, L. and Lopez-Juez, E. (2008). Light fluence rate and chloroplast are sources of signal controlling mesophyll cell morphogenesis and disvision. *Cell Biology International*, 32: 363-565

Theis, J. and Grady, H.M., (1991). *Participatory Rapid Appraisal for Community Development: A Training Manual Based on Experience in the Middle East and North Africa*. IIED / Save the Children Foundation, London.

Thompson, T. (2000). Questionable foods and the gluten - free diet: Survey of current recommendations. *The Journal of the American Dietetic Association*, 100: 463- 465.

Tiecher, T.; Rheinheimer, D.S.; Kaminski, J. & Calegari, A. (2012). Forms of inorganic phosphorus in soil under different long term soil tillage systems and winter crops. *Revista Brasileira de Ciência do Solo*, 36:271-281.

University of Ghana http://ugspace.ug.edu.gh

Till, B.J., Reynolds, S.H., Weil, C., et al. (2004b). Discovery of induced point mutations in maize genes by TILLING. *BMC Plant Biology*, 4:12.

Till, B. J., Cooper, J. and Tai, T. H. et al., (2007). Discovery of chemically induced mutations in rice by TILLING. *BMC Plant Biology*, 7:19.

Tiryaki, I. and Andrews, D. (2001). Germination and seedling cold tolerance in sorghum; *Crop Science*, 42:1391–1397.

Tossah, B.K. (2000). Influence of Soil Properties and Organic Inputs on Phosphorus Cycling Herbaceous Legume-based Cropping Systems in the West African Derived Savanna. Leuven, Belgium. Catholic University Leuven. PhD dissertation.

Tropical Soil, Biology and Fertility [TSBF] (1993). Handbook of methods. JM Anderson and SJ Ingram (Eds). CAB International, Oxon, UK.

Tucker, M. R. (1999). Essential plant nutrients, their presence in North Carolina soils and role in plant nutrition. Agronomic Division. NCDA and CS. [Online] Available: http://www.ncagr.gov/agronomi/pdffiles/essnutr.pdf. Accessed on 15th September 2010.

Turner BL, Papházy MJ, Haygarth PM, McKelvie ID (2002) Inositol phosphates in the environment. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 357: 449–469.

Turner B. L., Newman S., Cheesman A. W., Reddy K. R. (2007). Sample pretreatment and phosphorus speciation in wetland soils. *Soil Science Society of America Journal*, 71: 1538–1546.

Twomlow, S.J. and Ncube, B. (2001). Improving soil management options for women farmers in Malawi and Zimbabwe: Proceedings of a Collaborators Workshop on the DFID-supported project 'Will Women Farmers Invest in Improving their Soil Fertility Management? Experimentation in a risky environment', 13–15 September 2000, ICRISAT, Bulawayo, Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics, Bulawayo, Zimbabwe.

Uematsu, H. and Mishra, A. (2010). Can Education Be a Barrier to Technology Adoption? Selected Paper prepared for presentation at the Agricultural & Applied Economics Association 2010 AAEA, CAES, & WAEA Joint Annual Meeting, Denver, Colorado, 25-27.

Undersander, D. (2003). Sorghums, Sudangrasses, and sorghum-Sudan hybrids. Univ. of Wisconsin Focus on Forage 5:5, Madison. http://www.uwex.edu/CES/crops/uwforage/SorghumsFOF.htm. Accessed on 26th May 2013.

USDA National Nutrient Database for Standard Reference, Release 24. 2011.

University of Ghana http://ugspace.ug.edu.gh

United States Department of Agriculture Agricultural Research Service [USDA-ARS] (2012). National Genetic Resources Program. Germplasm Resources Information Network - (GRIN). National Germplasm Resources Library, Beltsville, MD, USA. [Online] Available at http://www.ars-grin.gov/cgi-bin/npgs/html/taxon.pl?35092.

Van Beuningen, L.T. and Busch, R.H. (1997). Genetic diversity among North American spring wheat cultivars: III Cluster analysis based on quantitative morphological traits. *Crop Science*, 97 (37): 981–988.

van der Velde, M., Folberth, C., Balkovic, J., Ciais, P., Fritz, S., Janssens, I. A., *et al*. (2014). African crop yield reductions due to increasingly unbalanced nitrogen and phosphorus consumption. *Global Change Biology*, 20, 1278–1288.

Van Harten AM (1998) Mutation Breeding: Theory and Practical Applications. Cambridge University Press, Cambridge, UK, 353.

Van Kauwenbergh, S.J. (2006). Fertilizer Raw Material Resources of Africa. Africa Fertilizer Summit. Abuja, Nigeria. IFDC R-16.

Vance, C. P. (2001) Symbiotic nitrogen fixation and phosphorus acquisition: Plant nutrition in a world of declining renewable resources. *Plant Physiology*, 127, 390–397.

Van Vuuren, D.P., Bouman, A.F. and Beusen, A.H.W. (2010). Phosphorus demand for the 1970-2100 period: a scenario analysis nod resource depletion. *Global Environmental Change*, 20: 428-439.

Vavilov, N.I. (1992). *Origin and geography of cultivated plants*. In: V.F. Dorofeyev (ed.), translated by D. Love. Cambridge University Press, Great Britain.

Veihe, A. (2002). The spatial variability of erodibility and its relation to soil types: a study from northern Ghana. *Geoderma*, 106 (1-2): 101-120.

Veneklaas E. J., Lambers H., Bragg J., Finnegan P. M., Lovelock C. E., Plaxton W. C., *et al*. (2012). Opportunities for improving phosphorus-use efficiency in crop plants. *New Phytologist*, 195: 306–32010.

Verde, B. and Matusso, J. (2014). Phosphorus in Sub-Sahara African soils – Strategies and options for improving available soil phosphorus in smallholder farming systems: A review. *Academic research journal of agricultural science and research*, 2 (1):1-15.

Verheye W. (2010). *Growth and production of sorghum and millets*. In: in Soils, Plant Growth and Production Volume II in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Vol. 2 Paris: Eolss Publishers;

University of Ghana http://ugspace.ug.edu.gh

Vom Brocke, K., G. Trouche, E. Weltzien, C. P. Barro-Kon-dombo, E. Goze´, and Chantereau, J. (2010). Participatory variety development for sorghum in Burkina Faso: farmers' selection and farmers' criteria. *Field Crops Research,* 119: 183–194.

Walkley, A. and Black, A.I. (1934). An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, 37:29-37

Wall, P. C., Neate, S.M., Graham, R.D., Reuter, D.J. and Rovira, A.D. (1994). The effect of rhizoctonia root disease and applied nitrogen on growth, nitrogen uptake and nutrient concentrations in spring wheat. *Plant and Soil,* 163: 111–120.

Wang, X., Shen, J. and Liao, H. (2010). Acquisition or utilization, which is more critical for enhancing phosphorus efficiency in modern crops? *Plant Science,* 179:302–306.

Wang, L., Lu, S., Zhang, Y., Li, Z., Du, X. and Liu, D. (2014) Comparative genetic analysis of Arabidopsis purple acid phosphatases AtPAP10, AtPAP12, and AtPAP26 provides new insights into their roles in plant adaptation to phosphate deprivation. *Journal of Integrative Plant Biology,* 56: 299 –314.

Wang S. K., Bai Y. H., Shen C. J., Wu Y. R., Zhang S. N., Jiang D. A., *et al.* (2010). Auxin-related gene families in abiotic stress response in *Sorghum bicolor*. *Functional Integrative Genomics* 10, 533–546.

Weaver, D.M. and Wong, M.T.F. (2011). Scope to improve phosphorus management and balance efficiency of crop and pasture soils with contrasting P buffer indices. *Plant and Soil* 349, 37-54.

Westengen, O. T., Okongo, M. A., Onek, L., Berg, T., Upadhyaya, H., Birke-land, S. *et al*. (2014). Ethnolinguistic structuring of sorghum genetic diversity in Africa and the role of local seed systems. *Proceedings of the National Academy of Sciences, USA,* 111: 14100–14105.

Whitehead, A. (2003). 'Policy Discourses on Women's Land Rights in Sub-Saharan Africa: The Implications of the Re-turn to the Customary'. *Journal of Agrarian Change*, 3 (1): 67–112.

White, P.J. and Veneklaas, E.J. (2012). Nature and nurture: the importance of seed phosphorus content. *Plant Soil,* 357:1–8.

Wissuwa, M, Kretzschmar, T, Rose, T.J. (2016). From promise to application: root traits for enhanced nutrient capture in rice breeding. *Journal of Experimental Botany,* 67: 3605-3615.

Wissuwa, M. and Ae, N. (2001). Genotypic variation for tolerance to phosphorus deficiency in rice and the potential for its exploitation in rice improvement. *Plant Breeding*, 120: 43–48.

University of Ghana http://ugspace.ug.edu.gh

Wissuwa, M., Wegner, J. and Ae, N. (2002) Substitution mapping of *Pup1*: A major QTL increasing phosphorus uptake of rice from a phosphorus-deficient soil. *Theoretical and Applied Genetics,* 105: 890–897.

Wissuwa M, Yano M, Ae N. (1998) Mapping of QTLs for phosphorus deficiency tolerance in rice (*Oryza sativa* L.). *Theoretical and Applied Genetics*, 97: 777–783

Wooten, D.R. (2001). The use of Sorghum propinquuto enhance agronomic traits in sorghum. M.S. Thesis. Texas A&M University, College Station, Texas.

Wu, J. L., Wu, C., and Lei C. *et al*., (2005). Chemical and irradiation-induced mutants of indica rice IR64 for forward and reverse genetics. *Plant Molecular Biology*, 59 (1): 85–97.

Xin, Z., Wang, M.L., Barkley, N.A., Burow, G., Franks, C., Pederson, G., Burke J. (2008). Applying genotyping (TILLING) and phenotyping analyses to elucidate gene function in a chemically induced sorghum mutant population. *BMC Plant Biology*, 8:103.

Xin, Z., Li, W., Ming, Burow, G. and Burke, J. (2009). An Induced Sorghum Mutant Population Suitable for Bioenergy Research. *BioEnergy Research*. 2:10-16.

Xin, Z., Gitz, D., Burow, G., Hayes, C., Burke, J.J. (2015). Registration of two allelic erect leaf mutants of sorghum. *Journal of Plant Registrations*, 9: 254–257.

Xin, Z., Huang, J., Smith, A.R., Chen, J., Burke, J., Sattler, S.E., *et al*. (2017). Morphological Characterization of a New and Easily Recognizable Nuclear Male Sterile Mutant of Sorghum (Sorghum bicolor). *PLoS ONE*, 12(1):e0165195.

Xu, Y. (2010). *Molecular plant breeding*. CAB International, Wallingford, UK.

Yahaya, A. and Amoah, S.A. (2013). Bushfires in the Nandom District of the Upper West Region of Ghana: Perpetual Threat to Food Crop Production. *Journal of the Environment and Earth Sciences*, 3 (7) 10-14.

Yamaguchi, M., Fujimoto, H.,Hirano, K., Nakamura, S.A.,Shinohara, K.O. *et al*. (2016). Sorghum Dw1, an agronomically important gene for lodging resistance, encodes a novel protein involved in cell proliferation. *Scientific Reports*, 6: 28366.

Yan L., Liu S., Zhao S., Kang Y., Wang D., Gu T., *et al*. (2012). Identification of differentially expressed genes in sorghum (*Sorghum bicolor*) brown midrib mutants. *Physiology of Plants*, 146: 375–387.

Yeshaneh, G. T (2015). Assessment of Farmers' Perceptions about Soil Fertility with Different Management Practices in Small Holder Farms of *Abuhoy Gara* Catchemnt, Gidan District, North Wollo. *American Journal of Environmental Protection*, 3 (4):137-144.

University of Ghana http://ugspace.ug.edu.gh

Ye X. D, Al-Babili, S., Kloti, A. Zhang, J., Lucca, P., Beyer, P. and Potrykus, I. (2000). Engineering the provitamin A (beta-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science,* 287:303-305.

Yilma T. (2006). Modeling farm irrigation decisions under rainfall risk in the White Volta Basin of Ghana. A tool for policy analysis at the farm-household level. Bonn, Göttingen, Germany: University of Göttingen, 170.

Yoneyama, K., Xie, X., Kusumoto, D., Sekimoto, H., Sugimoto, Y. and Takeuchi, Y. (2007b) Nitrogen deficiency as well as phosphorus deficiency in sorghum promotes the production and exudation of 5-deoxystrigol, the host recognition signal for arbuscular mycorrhizal fungi and root parasites. *Planta*, 227:125–132.

Young, K.J. and Long, S.P., (2000). *Crop ecosystem responses to climatic change: maize and sorghum*. In: Reddy, K.R., Hodges, H.F. (Eds.), Climate Change and Global Crop Productivity. CABI Publishing, Wallingford, 107–131.

Zhang, F., Shen, J., Zhang, J., Zuo, Y., Li, L., Chen, X. (2010). Rhizosphere processes and management for improving nutrient use efficiency and crop productivity: implications for China. *Advances in Agronomy*, 107: 1–32.

Zhao, J., Paulo, M.J., Jamar D, Lou P, van Eeuwijk F, Bonnema, G., Vreugdenhil, D., Koornneef, M. (2007). Association mapping of leaf traits, flowering time, and phytate content in *Brassica rapa*. *Genome*, 50: 963–973.

Zhao, J., Mantilla Perez, M.B., Hu, J. and Salas Fernandez, M.G., (2016). Genome-Wide Association Study for Nine Plant Architecture Traits in Sorghum. *The Plant Genome*, 9 (2).

Zhu, J.M. and Lynch, J.P. (2004). The contribution of lateral rooting to phosphorus acquisition efficiency in maize (*Zea mays*) seedlings. *Functional Plant Biology*, 31: 949–958.

Zohary, D., and M. Hopf. 2000. *Domestication of Plants in the Old World*, 3rd edition. Oxford: University Press.

Zomer, R.J., Trabucco, A., Coe, R., Place, F. (2009). Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper 89. Nairobi, Kenya: World Agroforestry Centre.

Zhou, K., Xia, J., Wang, Y., Ma, T., & Li, Z. (2017). A *Young Seedling Stripe2* phenotype in rice is caused by mutation of a chloroplast-localized nucleoside diphosphate kinase 2 required for chloroplast biogenesis. *Genetics and Molecular Biology*, 40 (3):630–642.

Zougmoré, R. (2003). Integrated water and nutrient management for sorghum production in semi-arid Burkina. Tropical resources management papers, 45, Wageningen University and Research center, Wageningen, the Netherlands. 205.

University of Ghana http://ugspace.ug.edu.gh

APPENDIX

Appendix 1: PRA questionnaire

Questionnaire number ----------

Name of interviewer ---------- Date----------

District---------- Community----------

Section A: **Background information**

1. Name of respondent:

   ……

2. Age range: 18-30 [ ] 31-45 [ ] 45-60 [ ] Above 60 [ ]

3. Gender: Male [ ] Female [ ]

4. Religion: Muslim [ ] Christian [ ] Traditional [ ] Other [ ] (Please specify)…….....

5. Level of education: Basic Education [ ] Secondary [ ] Tertiary [ ] None [ ]

6. Marital status: Married [ ] Single [ ] Divorced [ ] Widowed [ ]

7. Number of children:

   ……

8. Main occupation……..

9. What is the main source of income for your family? Farming [ ] Artisanship [ ]

University of Ghana http://ugspace.ug.edu.gh

Trading [ ] Casual labourer [ ] Others [ ]

10. Do you own your farm land? Yes [ ] No [ ]

Section B: Sorghum importance, production and constraints

11. Which crops you grow on your farm? Millet [ ] Sorghum [ ] Groundnuts [ ] Yam [ ] Cowpea [ ]

12. Which crop provides the most revenue? Millet [ ] Sorghum [ ] Groundnuts [ ] Yam [ ] Cowpea [ ]

13. How long have you been growing sorghum? Up to 5 years [ ] 6-10 years [ ] 11-15 years [ ] Over 15 years [ ]

14. Which sorghum varieties do you grow? Kapaala [ ] Naga white [ ] Belko [ ] Naga red [ ] Other [ ] Please specify ……..

15. Which is your most-preferred variety? .....

16. Why do you prefer this variety? …….

17. Why do you grow sorghum? Household use only [ ] Income only [ ] Both [ ]

18. What is the total size of your farm? ……

19. What proportion of your total land area is allocated to sorghum cultivation? .....

20. What is your estimated grain yield? .....

21. What problems do you face with sorghum cultivation?

University of Ghana http://ugspace.ug.edu.gh

…….

22. Which of these problems are you most concerned about? List them in order of importance.

Production constraints	Please tick all that apply	Ranking
Lack of sufficient rain		
Pests (insects, birds, etc.)		
Diseases		
High cost of inputs		
Land unavailability		
Declining soil fertility		
Weeds		
Post-harvest losses		
Lack of seed		
Other …….		

23. Where do you obtain your sorghum seeds from? Self/saved seeds [ ] Local market [ ] Other farmers [ ] NGOs [ ] Family [ ] Others [ ] Please Specify

24. Do you receive agricultural information (new technologies, improved seeds, fertiliser subsidies, etc.) regularly? Yes [ ] No [ ]

25. If yes, what are the sources of such information? Agric. extension officers [ ] NGOs [ ] Radio [ ] Television [ ] Research institutions [ ]

Section C: Farmers' knowledge, attitudes and perception of soil fertility

1. Can you identify fertile and poor soils? Yes [ ] No [ ]
2. How can you tell if soil is fertile? Soil color [ ] Soil moisture [ ] Soil texture [ ] Crop performance [ ]

University of Ghana http://ugspace.ug.edu.gh

3. What causes soil infertility? Continuous cropping [ ] Insufficient rain [ ] Type of crop cultivated [ ]
4. How will you describe the land on which you grow sorghum in terms of fertility?

   Highly fertile [ ] Moderately fertile [ ] Poor [ ]
5. How can you improve the fertility of your farmland?.....
6. Do you apply fertiliser to sorghum? Yes [ ] No [ ]
7. If yes, why? …….
8. If no, why not? …….
9. If yes, which type of fertiliser do you use? Organic [ ] Inorganic [ ] Both [ ]
10. If organic, which type do you use? Animal droppings/manure [ ] Compost/mulch [ ]
11. If inorganic, which type do you use? …….
12. When do you apply the fertiliser to the crop? At planting [ ] One month after planting [ ] Two months after planting [ ] Whenever I obtain some [ ]
13. How many bags of fertiliser do you apply to your sorghum crop? 1 bag [ ] 2 bags [ ] 3 bags [ ] 4 bags [ ] Other [ ] Please specify……
14. How often do you apply fertiliser? Once in the growing season [ ] Twice in the growing season [ ] Other [ ] Please specify……...
15. What factors affect your use of fertiliser? Cost [ ] Availability [ ] Lack of access to credit [ ] Other [ ] Please specify…….

University of Ghana http://ugspace.ug.edu.gh

16. Do you think soil infertility affects sorghum? Yes [ ] No [ ]
17. If yes, how does it affect the crop? Reduced yield [ ] Stunted growth [ ] Poor seedling establishment [ ] Discolouration of leaves [ ] Other [ ]
18. Which of these cropping systems do you practice? Mono-cropping [ ] Crop rotation [ ] Intercropping [ ] Mixed cropping [ ]
19. Do you practice any of these? Shifting cultivation [ ] Retention of crop residue [ ] Erosion control [ ]

5. If yes, which erosion control measures do you use on your sorghum farm?

   Cover cropping [ ] Stone bunding [ ] Earth bunding [ ] Ridging [ ] Grass strips [ ]

Section D: Farmers' preference for traits

1. What traits do you prefer in a sorghum variety?

   .....

University of Ghana http://ugspace.ug.edu.gh

2. List them in order of importance.

Preference criteria	**Tick all that apply**	**Ranking**
Early maturing		
High yielding		
Adaptation to poor soils		
Drought tolerance		
Grain quality (taste, brewing, cooking, etc.)		
Tolerance to diseases		
Tolerance to pests (birds, striga, aphids, etc.)		
Resistance to lodging		

University of Ghana http://ugspace.ug.edu.gh

Appendix 2: p- values for Pearson's correlation coefficient of quantitative traits among 550 genotypes

Variables	PL	PE	PW	PH	DTF	NL	SG	HSW	GYP
PL	**0**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.944	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
PE	**< 0.0001**	**0**	**< 0.0001**	0.178	0.655	**< 0.0001**	**< 0.0001**	0.229	**< 0.0001**
PW	**< 0.0001**	**< 0.0001**	**0**	**< 0.0001**	**0.010**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
PH	**< 0.0001**	0.178	**< 0.0001**	**0**	0.304	**< 0.0001**	**0.004**	**< 0.0001**	**< 0.0001**
DTF	0.944	0.655	**0.010**	0.304	**0**	0.545	**0.013**	0.146	0.215
NL	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.545	**0**	**< 0.0001**	**< 0.0001**	**< 0.0001**
SG	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.004**	**0.013**	**< 0.0001**	**0**	**0.000**	**< 0.0001**
HSW	**< 0.0001**	0.229	**< 0.0001**	**< 0.0001**	0.146	**< 0.0001**	**0.000**	**0**	**< 0.0001**
GYP	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.215	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0**

University of Ghana http://ugspace.ug.edu.gh

Appendix 3: Members of individual clusters in Figure 4.5

Cluster	Members of the cluster								
Cluster I	Mut0984	Mut0988	Mut1456#1	Mut2461	Mut0676	Mut1315	Mut0064	Mut1148	Mut0181#2
	Mut0767	Mut0640	Mut0641	Mut0696	Mut1156	Mut2204#1	Mut3312	Mut0662	Mut0321#1
	Mut0758	Mut0937	Mut0701	Mut2246#1	Mut1408#1	Mut4791#1	Mut0118	Mut0452#1	Mut0182
	Mut0058	Mut1206	Mut1202	Mut1721#2	Mut2245#1	Mut0457#1	Mut0454#1	Mut1875	Mut1300#1
	Mut1249	Mut1457#1	Mut1455#1	Mut0933	Mut0657	Mut1401#1	Mut0518-2	Mut1663#1	Mut2098#1
	Mut1204	Mut1508#2	Mut1768	Mut0509	Mut0459#1	Mut1820	Mut1865	Mut0814	Mut1610
	Mut1767	Mut1727	Mut1725	Mut1453#1	Mut1154	Mut3315	Mut0062	Mut0579	Mut0839#2
	Mut0992	Mut0986	Mut3161	Mut1773	Mut1817-2	Mut0683	Mut1666	Mut0437#1	Mut0006
	Mut0626	Mut0753	Mut1027#1	Mut1555#2	Mut1716	Mut1149	Mut0589	Mut1146	Mut2157
	Mut1248	Mut0516	Mut0935	Mut1044	Mut0623	Mut1399#1	Mut0116	Mut0577	Mut1253
	Mut1766-2	Mut1204#2	Mut1201	Mut0651	Mut0176	Mut1821-2	Mut0453#1	Mut0398#1	Mut1986#1
	Mut1113#1	Mut0257#1	Mut0122	Mut2854#1	Mut3708	Mut2309	Mut2711	Mut3466	Mut2038#1
	Mut2095#1	Mut0251#1	Mut0258#1	Mut3008	Mut3766	Mut3966	Mut3222	Mut3267	Mut0883
	Mut0811	Mut1294#1	Mut1252	Mut3011#1	Mut4260-2	Mut3857	Mut3962#1	Mut4016#1	Mut0538
	Mut0397#1	Mut2088#2	Mut2037#1	Mut3710	Mut4512	Mut3155	Mut4061#1	Mut4365	Mut2853#2
	Mut1303#1	Mut1609	Mut0885	Mut3813	Mut2616	Mut2663	Mut4406#2	Mut2410	Mut3010
	Mut2094#1	Mut0060	Mut0536	Mut2853#1	Mut2852#1	Mut2311	Mut4461	Mut5159	Mut3709
	Mut0817	Mut1297#1	Mut0256#1	Mut3812	Mut4015#1	Mut3611	Mut2666#2	Mut3862	Mut3814
	Mut3472	Mut1937#1	Mut2155#1	Mut4258	Mut4158	Mut3964#1	Mut3658	Mut4261	Mut4214
	Mut0369#1	Mut1608	Mut1251	Mut2619	Mut2900#1	Mut4308	Mut2250#1	Mut4361#2	Mut2660
	Mut0396#1	Mut0880	Mut2149#1	Mut3711#2	Mut2571	Mut2517	Mut3815	Mut2362	Mut3412
	Mut1100	Mut0301#1	Mut0329#1	Mut4161-2	Mut2901#1	Mut2714	Mut4060#1	Mut2807	Mut2857#1
	Mut1879#1	Mut1938#1	Mut0630	Mut4107#1	Mut2810	Mut3269	Mut3470	Mut3217	Mut3760#2
	Mut2093#1	Mut2040#1	Mut3053	Mut3003#1	Mut2359	Mut3612	Mut4967	Mut3863	Mut3808
	Mut1047	Mut0124	Mut3564	Mut3108	Mut3565	Mut2518	Mut2808	Mut3915	Mut2576
	Mut1302#1	Mut0007	Mut2661	Mut3715	Mut4013#1	Mut2952#1	Mut2950#1	Mut2513	Mut5095
	Mut1930#1	Mut2198#1	Mut3042	Mut3809	Mut4310	Mut2306	Mut4404	Mut3415	Mut2858#1
	Mut2091#1	Mut0542	Mut3763	Mut2575	Mut2572	Mut3657	Mut3468	Mut2806	Mut2955#1
	Mut1611	Mut0123	Mut3765	Mut4625	Mut2809-2	Mut4062#1	Mut2954#1	Mut3864	Mut2759

University of Ghana http://ugspace.ug.edu.gh

Mut0818	Mut0271#1	Mut2262	Mut3568	Mut2903#1	Mut4410	Mut4057#1	Mut3914	Mut2251#1
Mut4414	Mut4508	Mut4063#1	Mut3659	Mut2307	Mut4465	Mut4367	Mut3414	Mut4363#2
Mut4309	Mut2665	Mut2360	Mut3268	Mut3610	Mut2313	Mut4459#2	Mut2805	BTx623
Mut3310	Mut2904#1	Mut2248#1	Mut4017	Mut4012#1	Mut2712	Mut3469	Mut3514	Tx631

Cluster II	Mut0982	Mut1405#1	Mut1614	Mut1989#1	Mut4211	Mut4156	Mut4509	Mut3262
	Mut2354	Mut1668	Mut0575	Mut0262#2	Mut4602#1	Mut3318#2	Mut3364	Mut2756
	Mut0008	Mut0671	Mut1613-2	Mut2034#2	Mut3368	Mut2899#1	Mut4110#2	Mut3859
	Mut0517	Mut1353#1	Mut1094	Mut1960#2	Mut4559#1	Mut3092	Mut4507	Mut4366
	Mut1509	Mut0664	Mut0588	Mut0889	Mut4259-2	Mut3761	Mut3366	Mut2457
	Mut1726	Mut3311	Mut1092	Mut1510	Mut4558#2	Mut4511	Mut2573	Mut2715
	Mut2463	Mut1352#1	Mut1935#1	Mut1557	Mut2617#2	Mut3362	Mut4264	Mut3213
	Mut0985	Mut1838	Mut0178	Mut2662	Mut3712	Mut2850#1	Mut0317	Mut3916
	Mut0936	Mut1665	Mut0179	Mut2358	Mut4219	Mut3058	Mut2574	Mut3419
	Mut0644	Mut0596	Mut2199#1	Mut3160	Mut3609	Mut4014#1	Mut0641	Mut3663
	Mut1724	Mut1348#1	Mut1607	Mut3009#1	Mut3110	Mut4312	Mut3157	Mut3517
	Mut0646	Mut1876#1	Mut0275#2	Mut4212	Mut3810	Mut4510	Mut2713	Mut4364
	Mut1200	Mut2097#1	Mut1564	Mut3112	Mut4554#2	Mut3363	Mut3959#2	Mut3707
	Mut1771-2	Mut1661	Mut1562	Mut2856#2	Mut2620	Mut2811	Mut4409	Mut3516
	Mut2205#2	Mut0576	Mut0180	Mut3007#1	Mut4549#1	Mut3057	Mut5850	Mut3512
	Mut0460#1	Mut1101	Mut0568	Mut4213	Mut3105	Mut3563	Mut4405	Mut0881
	Mut2757	Mut4411#2	Mut3520	Mut3162	Mut3515-2			

University of Ghana http://ugspace.ug.edu.gh

Cluster III	Mut1504	Mut4768#1	Mut0674	Mut0394#1	Mut1254	Mut3094	Mut4105	Mut0121
	Mut0764#2	Mut1043#1	Mut0682	Mut1305#1	Mut1984#1	Mut4557#1	Mut3963#1	Mut5115
	Mut0120	Mut0647	Mut0456#1	Mut1658#2	Mut2039	Mut3004#1	Mut4106#1	Mut2716
	Mut1458#1	Mut0697	Mut1884	Mut0393#1	Mut0882	Mut4159	Mut2363	Mut3860
	Mut1505	Mut1199	Mut2203#1	Mut1877#1	Mut1561	Mut3567	Mut2409#2	Mut4460
	Mut0755	Mut0932	Mut1669	Mut0323#1	Mut1150	Mut4313-2	Mut5398#1	Mut3434
	Mut0643	Mut1774	Mut0672	Mut0005	Mut1991#1	Mut2570	Mut3960#1	Mut3662
	Mut0001	Mut1046	Mut4848	Mut1931	Mut2147#1	Mut3762	Mut4463	Mut3218
	Mut0514	Mut0931	Mut2247-2	Mut0059	Mut0395#1	Mut4155	Mut2949#1	Mut5199
	Mut0700	Mut0678	Mut2142#1	Mut0878	Mut1250	Mut4112	Mut2404	Mut5588
	Mut0512	Mut2205#1	Mut0056	Mut0580-2	Mut1992#1	Mut4311-2	Mut3158	Mut3911#2
	Mut1454#1	Mut0652	Mut1147	Mut0316#1	Mut3764	Mut2902#1	Mut2514	Mut3221
	Mut1769	Mut0679	Mut1350#1	Mut2041#1	Mut4218	Mut4108#1	Mut4059#1	Mut2761
	Mut1041#1	Mut0458#1	Mut0002	Mut0561	Mut1864	Mut3115	Mut4058#1	Mut3220
	Mut0934	Mut1818-2	Mut0813	Mut0061#2	Mut3005	Mut2906#1	Mut2364#2	Grinkan

University of Ghana http://ugspace.ug.edu.gh

Appendix 4: Procedures for soil characterization and analysis

Bulk density

Core samplers of approximately 75mm long and 75 mm internal diameter were driven into the soil until the top edge of the sampler was a few a millimeters below the soil surface and the inner cylinder was filled. The sampler was carefully removed in order to preserve the samples. The two cylinders were separated, retaining the 'undisturbed' soil in the inner cylinder. Metal disks were placed at each end of the cylinder and placed in a plastic bag. The process was repeated with other cores in close proximity so obtain 3 replicates. Soil samples were transported to the laboratory carefully and oven-dried at 105^{o}C for 24 hours. The weight of the oven-dried samples was noted. The volume of the core sampler was estimated using the diameter and height. Bulk density was calculated using the following formula.

Bulk density (Mg/m^3) = Mass of dry soil (g)/ Volume of core (cm^3)

Particle size distribution

One hundred ml of 5% calgon (sodium hexametaphosphate) was added to 40 g of fine earth fraction of soil in a plastic bottle. The content of the bottle was thoroughly mixed on a mechanical shaker for 2 hours. The mixture was then transferred to a measuring cylinder and topped to the 1 litre mark. The suspension was then agitated for 5 minutes after which the density was measured using a hydrometer. Measurement of the density of the suspension was repeated after 8 hours. Temperature of the suspension during the 5 minute and 8 hour hydrometer readings was recorded as T_1 and T_2. The contents of the cylinder were emptied into a sieve of pore size 47 µm. The soil sample (sand) retained on the sieve was washed and dried for 24 hours at 105^{o}C. Subsequently, the dry weight of the sand was recorded. Blank sample hydrometer readings at 5 minutes and 8

University of Ghana http://ugspace.ug.edu.gh

hours were also recorded for the 5% calgon. Particle size distribution was then determined using the formula below;

% clay and silt = (5 minute reading – correction for temperature) / oven dry sample x 100

% clay = (8 hour reading – correction for temperature) / oven dry sample x 100

% silt = % clay and silt - % clay

% sand = (oven dry weight of particles retained on the sieve)/ oven dry mass of sample x 100

The effect of temperature on density of the soil particles was accounted for using the relation provided by Day (1965). For every 1 ^{o}C increase in temperature above 19.5 ^{o}C, there is an increase of 0.3 in the density of the particles in suspension.

Correction for temperature = blank hydrometer reading – increase in weight of particles

Soil moisture at field capacity

A 500 g soil sample was saturated with water in a filter paper-lined perforated plastic container of 15 cm in diameter and 20 cm in height. The plastic container was covered to prevent evaporation and allowed to drain for 3 days. The soil sample was oven-dried at 105 ^{o}C for 24 hours. The moisture content of the soil sample at field capacity was determined as the difference in mass between moist soil and oven-dried soil.

Soil pH

Ten millilitres of distilled water was added to 10 g of soil was to form a suspension. The suspension was stirred vigorously and allowed to stand for 30 minutes. The pH was measured by inserting the microprocessor pH 213 meter into the supernatant of the soil solution.

University of Ghana http://ugspace.ug.edu.gh

Soil organic carbon

This was determined using the wet combustion method (Walkley and Black, 1934). Soil sample was prepared by sieving through a 0.5 mm sieve. In an Erlenmeyer flask, 10 ml of 0.167 M dichromate ($K_2Cr_2O_7$) solution and 20 ml of sulphuric acid was added to 0.5 g of the sieved soil. The flask was swirled after which the mixture was allowed to stand for 30 minutes. The unreduced $K_2Cr_2O_7$ in the sample was titrated with 0.2 M ferrous ammonium sulphate solution. The bright green end point was reached after the addition of 10 ml of orthophosphoric acid and 2 ml of barium diphenylamine sulphonate indicator. A standardized titration of the $K_2Cr_2O_7$ with ferrous ammonium sulphate was also done. The amount of organic carbon was calculated as the difference between the number of moles of $K_2Cr_2O_7$ present in the standardized titration and the number of moles of the unreduced $K_2Cr_2O_7$.

Total nitrogen

Total N of the fine earth was determined by using the Kjeldahl digestion procedure (Anderson and Ingram, 1998). In a digestion tube, 5 ml of concentrated sulphuric acid was added to1 g of fine earth. The mixture was heated for 30 minutes after which 2 ml of hydrogen peroxide was added. The temperature was increase to 360 ^{o} C and maintained till the mixture was a colourless solution. Distilled water was added to the cooled digest to the top of a 100 ml volumetric flask. Twenty millilitres of the digest was transferred to a distillation flask followed by the addition of 10 ml of 40 % NaOH. After distillation, the ammonia released was condensed and

University of Ghana http://ugspace.ug.edu.gh

Total and available phosphorus

This was determined by the Bray1method (Bray and Kurtz, 1945). Fifty millilitres of Bray's extractant (0.03 M NH_4F and 0.025 M HCl) was added to 5 g of soil sample. The mixture was shaken for 5 minutes and allowed to stand. The supernatant was passed through filter paper in order to obtain a clear solution. For colour development, a drop each of P-nitrophenol and ammonium hydroxide was added to 1 ml of the clear sample solution in a volumetric flask.

Total phosphorus was determined by digesting biochar (0.2 g) with 25ml of a mixture of HNO_3 and 60% $HClO_4$ in a ratio of 1:1:5. Distilled water was added to the filtered digest to a volume of 100 ml. The amount of phosphorus in the digest was determined as described by Murphy and Riley (1962) and the P concentration calculated.

Exchangeable bases

In an extraction bottle, 50 ml of 1 M ammonium acetate was added to 5 g of fine earth. The solution was then filtered through Whatman filter paper. Calcium and magnesium levels in the extract was determined using an atomic absorption spectrophotometer while sodium and potassium levels were estimated on a flame photometer.

Appendix 5: Determination of phosphorus in leaf and grain samples

Leaf and grain samples were analysed for P content were milled separately in a blender. Total digestion was carried on one gram of ground plant material using the Bhargava and Raghupathi (1984). Aliquots of the resultant solutions were used for the determination of P concentration. P concentration (total amount of phosphorus) in the plant samples in mg/g was determined using the Murphy and Riley (1962) method. The same protocol was used for determining P concentration in grain samples.

University of Ghana http://ugspace.ug.edu.gh

Appendix 6: Names of putative mutants (codes) used in PCA biplot of 200 genotypes as shown in Figure 5.3

Genotype	Code	Genotype	Code	Genotype	Code	Genotype	Code	Genotype	Code
Mut1727	M1	Mut4107#1	M41	Mut2572	M81	Mut2250#1	M121	Mut0058	M161
Mut3108	M2	Mut2620	M42	Mut4012#1	M82	Mut4060#1	M122	Mut0120	M162
Mut2463	M3	Mut3779	M43	Mut4108#1	M83	Mut4967	M123	Mut0056	M163
Mut0936	M4	Mut3003#1	M44	Mut2573	M84	Mut2950#1	M124	Mut0460#1	M164
Mut1455#1	M5	Mut3809	M45	Mut3115	M85	Mut3468	M125	Mut0056	M165
Mut1769	M6	Mut4625	M46	Mut2665	M86	Mut2954#1	M126	Tx430	Tx430
Mut1771-2	M7	Mut3568	M47	Mut2309	M87	Mut3262	M127	CSM63	CSM63
Mut2205#2	M8	Mut2857#1	M48	Mut3857	M88	Mut4459#2	M128	TxARG1	TxARG1
Mut1817-2	M9	Mut3105	M49	Mut4264	M89	Mut3469	M129	FeteritaGishesh	FeteritaGishesh
Mut1669	M10	Mut3760#2	M50	Mut0317	M90	Mut3659	M130	Tx631	Tx631
Mut0454#1	M11	Mut3808	M51	Mut2574	M91	Mut3268	M131	ICSV1049	ICSV1049
Mut1665	M12	Mut2858#1	M52	Mut3964#1	M92	Mut5115	M132	BN223	BN223
Mut0393#1	M13	Mut2955#1	M53	Mut4105	M93	Mut3859	M133	Tx2752	Tx2752
Mut1614	M14	Mut3708	M54	Mut4308	M94	Mut4017	M134	SC599	SC599
Mut0369#1	M15	Mut3766	M55	Mut2517	M95	Mut4366	M135	Tx436	Tx436
Mut1254	M16	Mut4156	M56	Mut3269	M96	Mut3466	M136	Framida	Framida
Mut1253	M17	Mut4260-2	M57	Mut3612	M97	Mut2716	M137	MR732	MR732
Mut0538	M18	Mut4512	M58	Mut4106#1	M98	Mut3267	M138	Mota Maradi	Mota Maradi
Mut0395#1	M19	Mut2616	M59	Mut2363	M99	Mut3860	M139	Segeolane	Segeolane
Mut3160	M20	Mut3318#2	M60	Mut2713	M100	Mut2410	M140	Sariaso	Sariaso
Mut3564	M21	Mut2852#1	M61	Mut2952#1	M101	Mut3434	M141	HoneyDrip	HoneyDrip
Mut3764	M22	Mut2899#1	M62	Mut2306	M102	Mut3213	M142	Grinkan	Grinkan
Mut3112	M23	Mut3092	M63	Mut3657	M103	Mut3862	M143	CE151262A1	CE151262A1
Mut2856#2	M24	Mut4015#1	M64	Mut3959#2	M104	Mut3916	M144	El-Mota	El-Mota
Mut4211	M25	Mut4313-2	M65	Mut4062#1	M105	Mut4361#2	M145	Wassa	Wassa
Mut3368	M26	Mut4511	M66	Mut4465	M106	Mut3419	M146	PI609567	PI609567

University of Ghana http://ugspace.ug.edu.gh

Genotype	Code	Genotype	Code	Genotype	Code	Genotype	Code	Genotype	Code
Mut3709	M27	Mut2570	M67	Mut2409#2	M107	Mut3663	M147	Ajabsido	Ajabsido
Mut4214	M28	Mut2850#1	M68	Mut2313	M108	Mut3217	M148	MDK	MDK
Mut3412	M29	Mut3762	M69	Mut5398#1	M109	Mut4364	M149	KuyumaWSV387	KuyumaWSV387
Mut2854#1	M30	Mut4155	M70	Mut3960#1	M110	Mut3415	M150	KoroKollo	KoroKollo
Mut3008	M31	Mut4510	M71	Mut4063#1	M111	Mut3707	M151	Sepon82	Sepon82
Mut3011#1	M32	Mut2571	M72	Mut4409	M112	Mut3218	M152	Theis	Theis
Mut3813	M33	Mut3363	M73	Mut2360	M113	Mut3864	M153	SC35	SC35
Mut4218	M34	Mut3057	M74	Mut2248#1	M114	Mut0881	M154	Seguetana	Seguetana
Mut4259-2	M35	Mut3563	M75	Mut3222	M115	Mut3414	M155	Kadaga West	Kadaga West
Mut1864	M36	Mut4112	M76	Mut5850	M116	Mut2757	M156	Mut0988	M166
Mut3005	M37	Mut4311-2	M77	Mut3962#1	M117	Mut3514	M157	Mut0839#2	M167
Mut3712	M38	Mut2902#1	M78	Mut4061#1	M118	Mut2759	M158	Mut2091#1	M168
Mut3810	M39	Mut2359	M79	Mut2404	M119	Mut1725	M159	Mut2098#1	M169
Mut4161-2	M40	Mut4310	M80	Mut3158	M120	Mut0001	M160	Mut0122	M170

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

Appendix 7: Distribution of 200 genotypes in three clusters – Figure 5.4

Cluster I	Mut1727	Mut1864	Mut2571	Mut4062#1	Mut3514	Mut3764	Mut3318#2	Mut4264
	Mut2463	Mut3810	Mut3363	Mut4465	Mut0056	Mut3112	Mut3092	Mut0317
	Mut1769	Mut2620	Mut4112	Mut2409#2	Mut0056	Mut2856#2	Mut4313-2	Mut2574
	Mut1771-2	Mut3568	Mut4311-2	Mut5398#1	Tx631	Mut4211	Mut2850#1	Mut4105
	Mut2205#2	Mut2857#1	Mut2902#1	Mut3960#1	SC599	Mut3762	Mut4308	Mut4366
	Mut1817-2	Mut3766	Mut4012#1	Mut4063#1	Mut3368	Mut4155	Mut4106#1	Mut3213
	Mut1614	Mut4156	Mut3115	Mut4409	Mut4214	Mut4510	Mut2713	Mut3218
	Mut0369#1	Mut4512	Mut3857	Mut5850	Mut4218	Mut3962#1	Mut3158	Mut2250#1
	Mut4017							
Cluster II	Mut3108	Mut0538	Mut4259-2	Mut3760#2	Mut3563	Mut3612	Mut4060#1	Mut3268
	Mut0936	Mut0395#1	Mut3005	Mut3808	Mut2359	Mut2363	Mut4967	Mut5115
	Mut1455#1	Mut3160	Mut3712	Mut2858#1	Mut4310	Mut2952#1	Mut2950#1	Mut3466
	Mut1669	Mut3564	Mut4161-2	Mut2955#1	Mut2572	Mut2306	Mut3468	Mut2716
	Mut0454#1	Mut3709	Mut4107#1	Mut3708	Mut4108#1	Mut2360	Mut2954#1	Mut3267
	Mut1665	Mut3412	Mut3779	Mut4260-2	Mut2665	Mut2248#1	Mut3262	Mut3860
	Mut0393#1	Mut2854#1	Mut3809	Mut2616	Mut3964#1	Mut3222	Mut4459#2	Mut2410
	Mut1254	Mut3008	Mut4625	Mut2852#1	Mut2517	Mut4061#1	Mut3469	Mut3434
	Mut1253	Mut3813	Mut3105	Mut2570	Mut3269	Mut2404	Mut3659	Mut3862
	Mut3916	Mut3663	Mut3415	Mut2757	Mut0001	Tx430	BN223	Framida
	Mut4361#2	Mut3217	Mut3864	Mut2759	Mut0058	TxARG1	Tx2752	MR732
	Mut3419	Mut4364	Mut3414	Mut1725	Mut0120	ICSV1049	Tx436	Grinkan
	CE151262A1	SC35	KuyumaWSV387	Mut0839#2	Mut2098#1			
	MDK	Mut0988	Sepon82	Mut2091#1	Mut0122			
Cluster III	Mut3011#1	Mut4015#1	Mut2573	Mut3959#2	Mut3707	CSM63	Segeolane	El-Mota
	Mut3003#1	Mut4511	Mut2309	Mut2313	Mut0881	FeteritaGishesh	Sariaso	Wassa

University of Ghana http://ugspace.ug.edu.gh

Mut2899#1 Ajabsido	Mut3057 KoroKollo	Mut3657 Theis	Mut3859 Seguetana	Mut0460#1 Kadaga West	Mota Maradi	HoneyDrip	PI609567

University of Ghana http://ugspace.ug.edu.gh