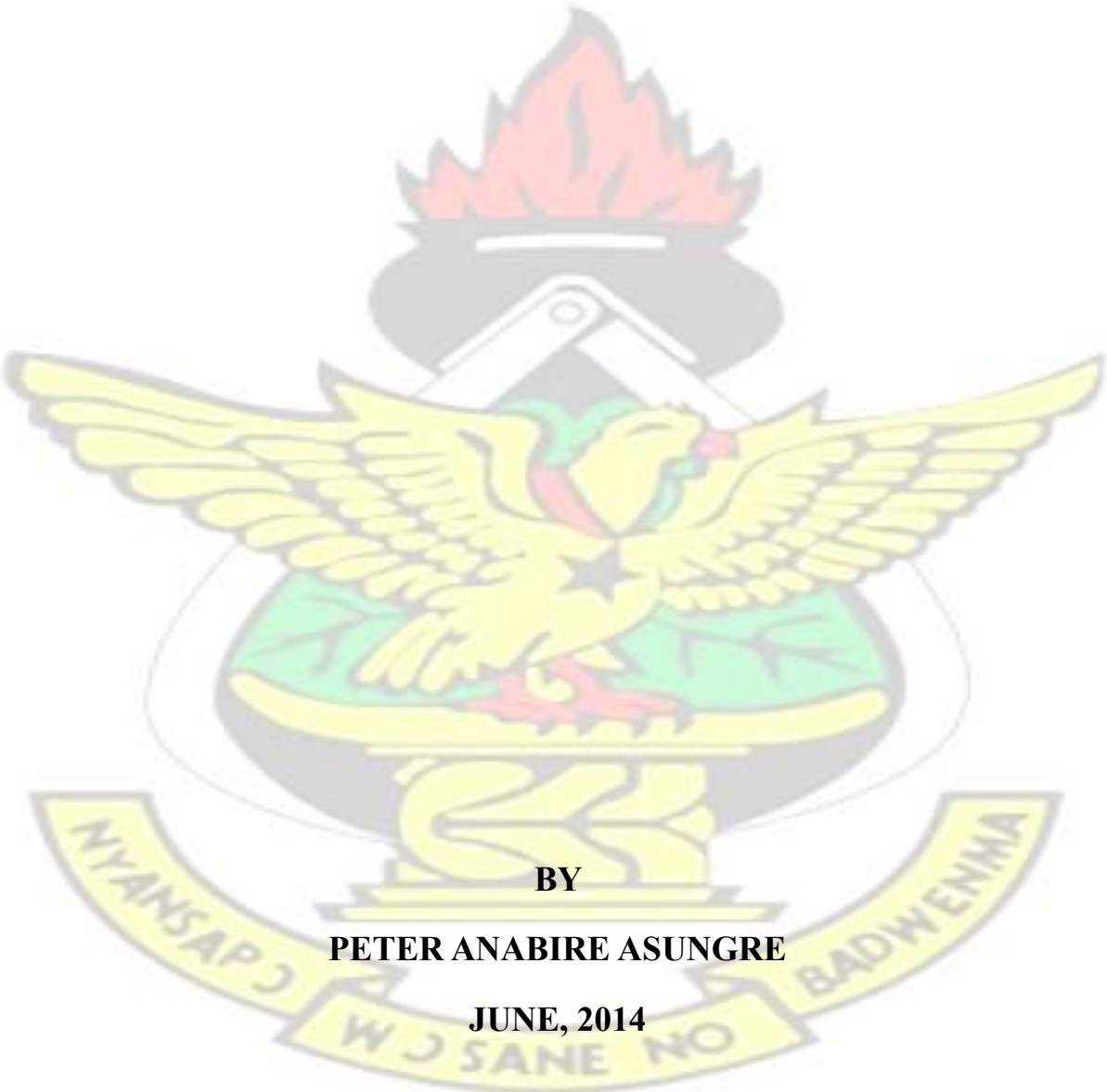
CHARACTERISATION OF PEARL MILLET [*Pennisetum glaucum*, (L), R.BR] GERMPLASM IN GHANA



BY

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JUNE, 2014

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DEPARTMENT OF CROP AND SOIL SCIENCES

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MASTER OF SCIENCE

IN

AGRONOMY (PLANT BREEDING)

JUNE, 2014

DECLARATION

I, Peter Anabire Asungre, hereby declare that, apart from references cited in relation to works done by other authorities, which have been duly acknowledged, this work is the result of my original research done under my supervisors. This thesis has neither in whole nor in part been presented for a degree elsewhere.

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ABSTRACT

Germplasm collections represent the store of genetic information available for crop breeding and improvement. Germplasm characterisation can be carried out by means of morphological, biochemical, or molecular analysis. Molecular analysis using genomic DNA is reliable since it can be carried out at any developmental state of plant and offers the opportunity to efficiently compare all accessions. The Simple Sequence Repeats (SSR) markers used have demonstrated to be very informative in studying relationships in closely related plant species as well as readily detecting co-dominant inheritance and exhibiting a high level of polymorphism per loci.

One hundred and twenty-six Pearl millet accessions were collected from Upper East, Upper West and Northern Regions which are home to Pearl millet production in Ghana. Days to 50 % booting separated 123 of the collections into Early, Medium and Late maturing groups whiles morphological data helped to further group the early maturity group into three clusters and five clusters each for medium and late maturity groups using Unweighted Pair-group Method with the Arithmetic Means (UPGMA) and Jaccard‘s coefficient range of 0-1.

Thirty-six Pearl millet SSR markers (loci) used to genotype 119 of the accessions collected, revealed an average of 8.8 alleles per locus. A maximum of 20 alleles were observed by loci Xpsmp2270 and Xpsmp2068, and a minimum of three alleles were revealed by loci XPsmp2246 and Xpsmp2201. Mean PIC, expected and observed heterozygosity values obtained indicate high polymorphism in the accessions. The sizes of alleles ranged from 98bp at locus Xpsmp2068 to 377bp at locus M13_Xpsmp2203. A combination of the molecular and morpho-agronomic data resulted in 30 (24.39%) accessions selected as core which could serve as trait-specific and local gene source for enhanced Pearl millet breeding work in Ghana.

DEDICATION

This work is dedicated to my Creator, God Almighty and my family.

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I am indebted to my employer (CSIR-Ghana) represented by the Director-General and Director of CSIR-SARI, for granting me the opportunity to further my studies and thus improve upon my knowledge base. The support, encouragement and contributions of fellow staff members have been overwhelming and I say thanks very much. I am very much grateful to Global Crop Diversity Trust (GCDT) for the financial support towards the collection and genotyping of the accessions. I am grateful to my main supervisor, Professor Richard Akromah, and my co-supervisor Dr. I.D.K Atokple, for working hard to ensure that this research work was done within the domain specified. The Senior Members of the Faculty of Agriculture, KNUST who availed themselves and offered free consultations and advices to enrich the final product deserve commendation. I am also grateful to the staff of

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To all well-wishers who contributed in all forms to help make this dream come true, I say thank you so much. All those who critiqued my presentation in a bid to fine-tune the research are highly acknowledged.

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TABLE OF CONTENTS

Page

LIST OF TABLES

Table

LIST OF FIGURES

Figure

Page

LIST OF APPENDICES

Appendix

Page

–

ACRONYMS

AFLP Amplified Fragment Length Polymorphism

AgSSIP – Agricultural Sub Sector Investment Project

ANOVA – Analysis of Variance

CGIAR – Consultative Group on International Agricultural Research

CRI – Crops Research Institute

CSIR – Council for Scientific and Industrial Research

DFB – Days to Fifty per cent Booting

DM – Downy mildew

DNA – Deoxyribonucleic Acid EST

– Expressed Sequence Tag

FAO – Food and Agricultural Organisation

GCDT – Global Crop Diversity Trust

HExp – Expected Heterozygosity

Hobs – Observed Heterozygosity

IARC – International Agricultural Research Centres

IBPGR – International Board for Plant Genetic Resources

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ICRISAT – International Crops Research Institute for the Semi-Arid Tropics

Acronyms

IFAD International Fund for Agricultural Development

IITA – International Institute for tropical Agriculture

IPGRI – International Plant Genetic Resources Institute

IRD – International Research and Development

ITCZ – Inter Tropical Convergence Zone

KNUST – Kwame Nkrumah University of Science and Technology

MAS – Marker-Assisted Selection

MoFA – Ministry of Food and Agriculture

NARP – National Agricultural Research Project

NARS – National Agricultural Research Systems

NBPGR – National Board for Plant Genetic Resources

NRC – National Research Centres OPVs

– Open Pollinated Varieties

PCR – Polymerase Chain Reaction

PGRFA – Plant Genetic Resources for Food and Agriculture

PGRRI – Plant Genetic Resources Research Institute

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PIC – Polymorphic Information Content

PPMED – Policy Planning Monitoring and Evaluation Directorate **Acronyms**

RAPD Random Amplified Polymorphic DNA

RFLP – Restriction Fragment Length Polymorphism

RHS – Royal Horticulture Society

RTIP – Root and Tuber Improvement Project

SAHN – Sequential Agglomerative Hierarchical Nested

SARI – Savanna Agricultural Research Institute

SAT – Semi-Arid Tropics

SNP – Single Nucleotide Polymorphism

SRID – Statistics Research and Information Directorate

SSR – Simple Sequence Repeat

UPGMA – Unweighted Pair-Group Method with the Arithmetic Means

USDA-USA – United State Department of Agriculture-United States of America

WIEWS – World Information and Early Warning System

CHAPTER ONE

1.1 Introduction

Millets are small-seeded grasses that are hardy and grow well in dry zones as rain-fed crops, under marginal conditions of soil fertility and moisture (FAO and ICRISAT, 1996), making them the preferred cereal crop in drier areas. Millets are one of the oldest food crops known to humans and possibly the first cereal grain to be used for domestic purposes (MilletEverything2. 2003).

The most widely cultivated species of millet in the world are Pearl millet (*Pennisetum glaucum* (L), R.Br), Foxtail millet (*Setaria italic* (L.) Beauv), Common or Proso millet (*Panicum miliaceum* L.), and Finger millet (*Eleusine coracana* L.). Species considered as minor include Barnyard millet (*Echinochloa frumentacea L.*), Kodo millet (*Paspalum scrobiculatum* L.), Little millet (*Panicum sumatrense Roth ex Roemer and Schulters*) and Fonio (*Digitaria exilis (Kippist) Stapf*) among others (Wikipedia, free encyclopaedia).

A Consultative Group on International Agricultural Research (CGIAR, 1996) report observed that conserving the rich diversity of crop varieties and related wild species is essential for providing farmers and plant breeders with raw material to improve and adapt crops to meet their future challenges such as climate change and diseases and pests upsurge. The need for genetic resource conservation has received a lot of attention by Food and Agriculture Organisation (FAO) of the United Nations (UN), working through other bodies including Bioversity International (BI), International Agricultural Research Centres (IARCs) and

National Agricultural Research Systems (NARS). Adaptive and productive agriculture depends on crop diversity as its ‗building block' which is being eroded due to inadequate funds for continuous and consistent collection and conservation (GCDT, 2012).

The CGIAR, through its network of International Agricultural Research Centres (IARC), maintains the world's largest international *ex situ*, or genebank collections of agrobiodiversity, comprising about 500,000 accessions (CGIAR, 1996). Efforts in the past have led to a significant increase in the number and size of plant genetic resource collections all over the world. Currently, World Information and Early Warning System (WIEWS) on Plant Genetic Resources for Food and Agriculture (PGRFA) and country reports, as captured in the State of the world report, 1996, indicate that about 7.4 million accessions of plant genetic resources are maintained globally, an increase of 1.4 million over the reported figure in the first state of the world report (GCDT, 2012),

Most farmers in Africa especially West Africa continue to plant traditional landrace cultivars while in Asia there is widespread promotion of hybrids and encouragement of the private sector to invest in seed production. The prospects for hybrid adoption in Africa remain unknown.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has core collections (10 % of entire collection) and mini core collections (10 % of the core or 1 % of entire collection) for all its mandate crops and finger millet, foxtail millet and proso millet to enhance use of germplasm in breeding programs. These core and mini core collections have been used to identify genetically diverse trait specific germplasm for resistance to abiotic and biotic stresses, and for agronomic and quality traits for use in breeding programs in the subregion. Collections kept at the various genebanks can be maintained under short-term (active collection stored at 4°C and 30 % RH) or long-term (base collection stored at –20°C in

vacuum packed aluminium foil pouches at 3-7 % seed moisture content and can be stored for more than 50 years) conditions with effective and regular monitoring. Regeneration may become necessary to ensure genetic integrity of the conserved collections using the appropriate plant population and pollination control methods (GCDT, 2012).

Collection missions had been carried out by SARI in the Upper East Region (between 2000 and 2004) during which 43 accessions were collected and sent to Plant Genetic Resources and Research Institute of Ghana (PGRRI) genebank (Bennett-Lartey and Oteng-Yeboah, 2008). These however lost their viability, after 10 years, when samples were called for by SARI and tested at Manga in June 2010. Also there was no comprehensive data accompanying these accessions. There was an earlier collection and evaluation work done in 1981 but was limited more to the early-maturing types as reported by Appa Rao *et al.,* (1985). The full genetic potential and diversity of these local landraces have not been explored.

Currently very insignificant database is available for the Ghanaian Pearl millet germplasm. This poses a challenge to conservationists and breeders in identifying and exploiting their inherent potentials. It is therefore important that a comprehensive database for Pearl millet grown in Ghana, showing their genetic variability, is developed, fine-tuned and made easily accessible to more scientists.

This study was therefore undertaken with the following main and specific objectives:

1.2 Main objective:

To collect and document Pearl millet diversity in Upper East, Upper West and Northern Regions of Ghana

1.2.1 Specific objectives were to:

1. assemble different Pearl millet accessions across the study area,
2. develop Agro-morphological characterisation database of the collected Pearl millet accessions,
3. genotype all the collected accessions using Simple Sequence Repeats (SSR) markers, and
4. identify and select a core collection for future breeding work.

CHAPTER TWO

2.1 Importance and uses of millet

Pearl millet is more tolerant to drought (Nouri *et al*., 2003) and low soil fertility than sorghum and it is an important food crop for the drier parts of Africa and India. It exists in a number of

distinct varieties or races exhibiting much variation and would appear to be amenable to considerable improvement (Webster and Wilson, 1989). The niche of the crop is in the semi-arid plains of Southern Asia (especially India) and the Sahel (Sub-saharan) region of Africa (David, 1981). It was introduced to Ghana by invaders from the north and its cultivation started at Ntesero in northern Ghana as early as 1250 B.C. (Davies, 1968). In Ghana Pearl millet is grown mainly as a food crop (yields are low, averaging only threequarters of sorghum yields in Africa and Asia) with the stalks used variously as fodder, roofing material, fencing material or source of saltpetre for cooking traditional food. Its ability to produce grain yield under hot, dry conditions and infertile soils with low waterholding capacity characteristic of northern Ghana, where other crops generally fail completely, has made it a preferred crop to start with immediately the rains set in. (CGIAR, 1996).

Pearl millet is reported to account for almost half of global millet production, with Africa recording 60% (estimated at 15 million hectares annually) and 14 million hectares in Asia (National Research Council, 1996). Global production of cultivated fields of Pearl millet exceeds 10 million tons. Pearl millet and Sorghum serve as main staple for more than 500 million people living in the semi-arid tropics (SAT), (NRC, 1996). Approximately 700 g per capita per day is consumed and this provides the bulk of dietary energy and protein for the consumers (James and Oppen, 1984). As a feed, grain Pearl millet is comparable to maize but superior to sorghum (Andrews *et al.,* 1993). Rooney and McDonough (1987) reported that Pearl millet was 1 to 2 percentage point higher in crude protein, 35 % more lysine and deficient in essential amino acids compared with sorghum. Ejeta *et al*. (1987) have also reported that _Pearl millet contains 27 – 32 % more protein than maize, higher concentrations of amino acids, twice the ether extract and higher gross energy than maize‘. Again, Jambunathan and Subramanian (1988) intimated that the proportion of germ in Pearl millet grain (17 %) was about double that of sorghum, while the endosperm accounted for 75 % as against 82 % in

sorghum. The afore-mentioned qualities of the Pearl millet makes it meet most of the nutrient requirements of its producers who are considered poor and deprived peasant farmers.

2.2 Classification and domestication of millet

Pearl millet is a cereal belonging to the genus *Pennisetum* which contains about 140 grassy tropical species. The four cultivated forms of Pearl millet are *typhoides* (found mainly in India and Africa), *nigritarum* (dominant in eastern Sahel), *globosum* (dominant in the western Sahel) and *leonis* (dominant on the West African coast) (Brunken *et al.,* 1977; Rai *et al.,* 1997; Syngenta, 2006). West Africa is reported to be the geographical centre of origin and domestication (about 3500 B. C. in Dhar Tichitt a Saharan site in Mauritania: Amblard and Pernes, 1989) of Pearl millet from where it was introduced into India around 2000 B.C. Hanna (1987), Rai *et al. (*1997), Gari (2002), Oumar *et al.* (2008), Tostain (1992), Tostain and Marchais (1993), and Rai *et al*. (1997), all seem to suggest that the likely regions of domestication of Pearl millet in Africa are Mauritania, Senegal and western Mali, but Harlan (1975), and Brunken *et al*. (1977) have reported that the crop was domesticated in Africa along the southern edge of the Sahara, west of the Nile around 3,000 to 5,000 years from where it spread to southern Asia. Pearl millet domestication in northern Ghana dates back to about 1459 BC as claimed by Birimi and reported by D'Andrea *et al*. (2001), and D'Andrea and Casey (2002).

2.3 Climate change and Pearl millet conservation

The main challenges for farmers within the semi-arid and arid tropics and sub-tropics are, yield instability, risk of crop failure and food insecurity. These challenges are as a result of erratic and unreliable rainfall during the cropping season (Kasei, 2001). According to Boyer (1982), drought is a major limiting factor to agriculture generally leading to reduction in crop yield. He

therefore indicated that, identifying genetic factors involved in plant response to drought stress is very significant and relevant for plant breeding. Kasei (2001) reported that the Upper-East Region of Ghana, although experiencing high annual rainfall figures of between 900-1120mm, is seriously affected by annual water loss through evapotranspiration with a high occurrence of site-specific drought spells and soils that possess poor water holding capacity. The Region and for that matter Ghana, is equally experiencing the impact of climate change and this has called for the need to rethink agricultural strategies used in Ghana.

The world has been experiencing increasing unstable climatic situation, resulting from global warming and greenhouse gasses emissions, in the last two or more decades (Akromah, 2012). This situation does not support efficient conservation of species and genes but rather serve to hasten gene erosion and species extinction. The rainfall pattern in West Africa is characterised by a significant north-south gradient (Very deep gradient with wide variations of between 15 % and 30% over short interval) due primarily to the movement of the Inter Tropical Convergence Zone (ITCZ) (André, 2008).

The Southward advancement of the Sahara desert in West Africa is thus making the environment drier with an accompanying adverse effect on plant genetic resources especially cereals like millet (Akromah, 2012). The food basket of the West African sub-region is seriously affected by climate change. In such situations the average yields of Pearl millet and Sorghum become rather unstable over years.

In other to cope with these poor growing conditions as well as food deficit, smallholder cereal grain cropping exists extensively in Sahelian West Africa where the average production of cereals is 80 % with an average growing period of 100 – 150 days (André, 2008). Many reports

including, Mangat (1992), and Ali *et al*. (2001), indicate that the performance of Pearl millet populations is greatly influenced by environment and genotype interactions. Hence, with the variations in the microclimates of the Sahelian sub-region it is expected that this will significantly influence major yield components of the crop as well as its distribution in the growing regions of Ghana in particular and West Africa as a whole. The threat of the Southward drift of Sahara desert is a pointer to the urgent demand for the preservation of local landraces to serve as major source of traits for effective breeding work.

2.4 Breeding work in Pearl millet

Pearl millet varieties with fairly high yield, tolerance to environmental stresses and disease and pest resistance are necessary in meeting the demands of the rural poor and subsistence farmers. Variety improvement has therefore remained a major goal of both national and international agencies and breeders (Wilson *et al*., 2008). In cognisance of the environmental effect on the crop, Pearl millet breeding programmes are located throughout diverse agroecological zones in sub-Saharan Africa with a lot of autonomy from one another.

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Jackson and McRae (1998), and Holland *et al*. (2002), alluded to the fact that germplasm developed within individual programmes often have superior performance within the region of selection. They however concluded that this may not hold true for some crops since research conducted with other crops suggest that greater gain and stability can be obtained when selecting for broader adaptability compared to site-specific performance. Broad adaptation however may not be a preferred goal in developing crops such as Pearl millet that are grown as landraces and in marginal production areas (Ceccarelli, 1996; Omanya *et al*., 2007). Also the genetic variation in some landraces is not adequate to support gainful selection (Niangado and Ouendeba,1987). This assertion was however challenged by Rai and Kumar (1994), who cited

popular and high yielding improved varieties (including Ex-Bornu), developed within African Pearl millet landraces through selection. Local landraces have been grown and maintained by peasant farmers over decades and hence are very well adapted to various biotic and abiotic challenges of the area. They therefore, serve as the richest source of germplasm for trait improvement in most crops including Pearl millet (Akromah, 2012).

2.5 Types of millet

Millet is basically put into two classes known as the Pearl millet and Minor millet.

2.5.1. Pearl millet **(*Pennisetum glaucum*)**

Figure 2.1: Types of Pearl millet (left to right: finger millet, Pearl millet & foxtail millet)

Source: everything2.com/title/Millet, 2003

Purseglove, (1985) reported that Pearl millet (*Pennisetum glaucum*) also known as spiked millet, bajra and bulrush millet, could be taken as a single species with a number of cultivated races. The greatest number of both wild and cultivated forms occurs in Western Africa, confirming it center of origin and hence the importance of the sub-region for a number of unrelated millet species grown for food worldwide (Andrews *et al*., 1993). It is an erect, tillering plant with height ranging from 0.5 to 4.0 meters. It has varying seed colours and average weight of a 1000 seed range from 2.5 to 14 g with a mean of 8 (Purseglove, 1985).

The *Pennisetum glaucum* group constitute about 90.93% (22,560 of 24,910) of the *Pennisetum* information available at GENSYS collections thus making it one of the most important groups to work with.

2.5.2. Minor millets

Consist of many types including finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), common or prove millet (*Panicum miliaceum*), little millet (*Panicum sumatrense*) and barnyard or sawa millet (*Echinochloa crus-galli and Echinochloa corona*). Though not very important in terms of world food production, they are essential as food crops in their respective agro-ecosystems where they have carved a niche and thus respond very well to marginal environments (Purseglove, 1985).

Finger millet **(***Eleusine coracana* L.) also known as African millet, with an average plant height of 0.40 to 1.0 meter and spike length of 3.0 – 13.0 centimeter, has its niche in parts of eastern and central Africa and precisely in northern and parts of western Uganda and northeastern Zambia and serves as a valuable grain for the beer industry in the region.

Foxtail millet **(***Setaria italica* L.) has the longest history (Heng-Sheng *et al*., 2012) and is the second most widely cultivated species of millet, especially in East Asia where it was domesticated together with Common millet **(***Panicum miliaceum* L.). Among the millet in Japan, Foxtail millet is the most important and in India the crop is widely cultivated and used for various purposes (Purseglove, 1985). It is a relatively shorter plant (1 to 1.5 m) even though on the average it is taller than Finger and common millets.

2.6 Botany of Pearl millet

Pearl millet is a monocot species belonging to the Poaceae family and has a relatively small diploid genome (2n=2x=14) with a DNA content of 1C 2.36 pg (Martel *et al*., 1997). Harlan and de Wet (1971) recognised three germplasm pools in respect of cultivated Pearl millet. These consist of primary pool containing all forms of cultivated, weedy, and wild diploid (2n = 14), the secondary pool which has solely *P. purpureum* (Shum.) (2n = 28) and the tertiary pool which consist of many more distantly related *Pennisetum species* of various ploidy levels. According to Dujardin and Hanna (1989, 1990) the tertiary gene pool do not naturally interbreed with the primary pool, even though this is potentially possible through various wide crosses which may not be very usefully for the breeder except under rear cases of trait search.

Pearl millet is a highly cross-pollinating crop (Open Pollinated Varieties, OPVs) which can reach as high as 85% (or more outcrossing rate due to the fact that it is protogynous: all the sessile flowers on each head are perfect) flowering and wind-borne pollination. Burton (1974), and Chirwa (1991), reported that about 20% selfing is normal with Pearl millet which therefore require carefulness in handling the crop during pollination. As an OPV, landrace Pearl millets are highly heterogeneous and hence morphologically more variable than singlecross hybrid millets (Rai *et al*., 2009). It is a cereal crop with high tillering ability to help it avert hash environmental stresses associated with its area of cultivation.

2.6.1 Morphology of the Pearl millet plant

Hanna (1990) and Dujardin and Hanna (1989) reported that Pearl millet is one of the most responsive crop species to breed. This is due to its _floral morphology, breeding behaviour and the structure of grain yield‘. They therefore concluded that _This makes it possible to access genetic variability both from the secondary and tertiary germplasm pools‘. According to Andrews *et al*. (1993) it is a highly tillering, cross-pollinating species (Self-pollination can

occur when stigma emergence on later flowering tillers overlaps with the anthesis of earlier heads on the same plant) with a perfect flower on each head. Grains (numbering between 500 and 3,000) are on the surface of erect candle shaped terminal spikes. Pearl millet appears to have relatively fast root development, sending extensive roots both laterally and downward into the soil profile to take advantage of available moisture and nutrients (info@jeffersoninstitute.org,). Pearl millet plants vary in panicle length, seed size, seed colour, and plant height, depending on the cultivars and environments (www.syngentafoundation .com/millet.htm).

2.7 Growth condition for Pearl millet

According to Virmani (1984), _The semi-arid tropics, following Troll's classification, are areas where monthly rainfall exceeds potential evapotranspiration for 2 to 7 months annually and the mean monthly temperature is above 18°C for most of the year. Within this climatic zone, the areas with 2 to 4.5 wet months are called the dry semi-arid tropics, and almost all the millet (> 90%) and most of the sorghum (>75%) are grown. In the millet production regions (Sahel region of Africa), solar radiation is relatively high throughout the year with high temperatures (Konate, 1984) which in themselves are not limiting factors to the production of the crop, even though they do strongly influence plant growth and development. The climate of the regions (Sahel region of Africa) is associated with amounts of precipitation that do not normally commensurate with the evaporative demand of the atmosphere. This is further worsened by an uneven seasonal distribution in precipitation.

Due to its short crop life cycle and rapid grain filling, coupled with its exceptional ability to tolerate drought (Burton, 1985), Pearl millet does well in arid regions that do not support

effective production of other cereals like sorghum or maize. The soils are mainly brown and sandy, low pH and low fertility, with volumetric water content ranging from 12 to 15% at field capacity and from 3 to 4% at wilting point. These soils, because of their coarse texture, are particularly suited to millet crops (Konate, 1984). Studies conducted by Cocheme and Franquin (1967), revealed that _even in the semi-arid zones too much water or excessively long wet periods can reduce production even in an adapted variety. Therefore, millet crop yields in the area are not necessarily more than average even if annual rainfall is above normal‘. Even though Pearl millet will respond to good soil fertility, it does not have a high nutrient demand (Robert, 1999) compared with maize and sorghum.

The average yield of traditional landrace millet on West African farmers‘ fields over years have been as low as 200 to 600 kg/ha depending on country and season (Virmani, 1984; Tanzubil and Yakubu, 1997) even though yields from research fields could be as high as 2000 kg/ha (Tanzubil and Yakubu, 1997). The low yield situation has been blamed on low erratic rainfall, inherent poor and degraded soil coupled with invasion and increased numbers of insects, diseases and weeds (Tanzubil and Mensah, 2000).

2.8 Pearl millet production zones in Ghana

Pearl millet is grown mainly in the three Administrative regions of Northern, Upper East Upper West (covering 29% total land area, Fig. 2.2) of Ghana, (SRID, 2011). Northern Ghana is located within the Sudan *and Guinea Savanna zones (*also known as semi-arid zone or interior Savanna) which cover about 41% of the land area of Ghana (Bennett-Lartey and Oteng-Yeboah, 2008). The regions are bounded to the north by Ivory Coast and Bukina Faso, to the east by Togo, the west by Cote D‘lvoire and to the south by Brong Ahafo Region.

Northern Ghana is characterised by a uni-modal type of rainfall which last between April/May and September/October with an annual mean ranging from 800 to 1,200 mm (Bennett-Lartey and Oteng-Yeboah, 2008). The mean rainfall for 10 and 30 year period (SRID, 2011) indicate that the amount declines from south to north as observed in Fig. 2.3.

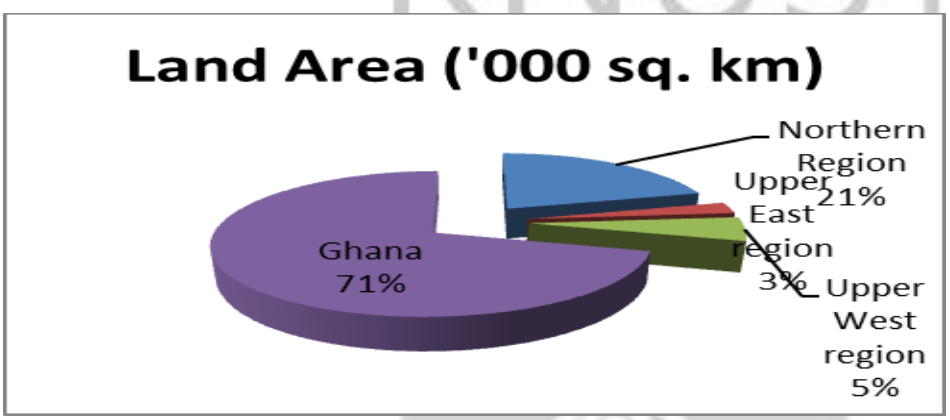

Figure 2.2: Total land area of regions covered

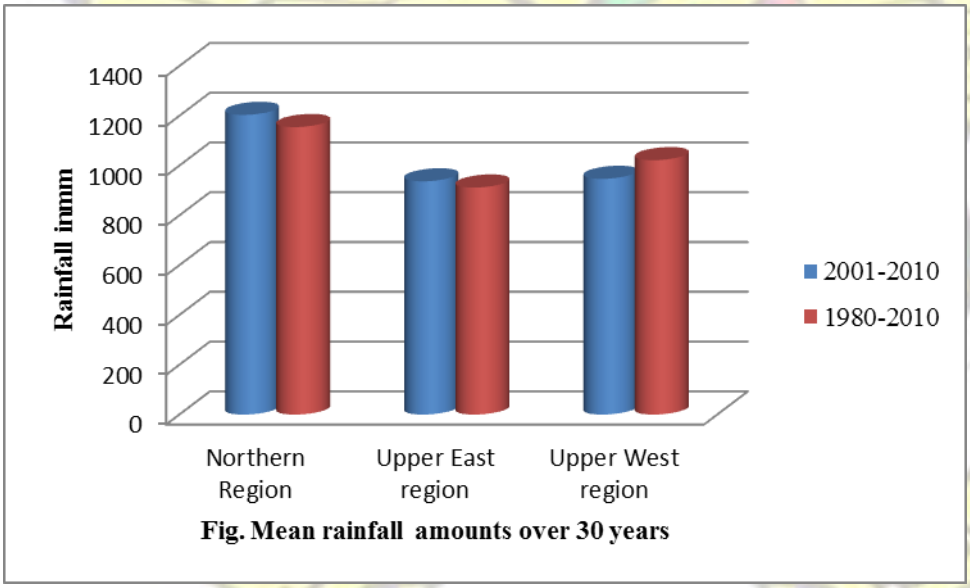

Figure 2.3. Mean rainfall amounts over 30 years in northern Ghana

Source: SRID, MOFA (2011)

Runge-Metzger (1993) describe the soils as ranging from granites interspersed with pyroclastic rock in Upper East to voltarian sandstone in the Northern region making them easy to work but prone to concretions and hardpan which affect their physical properties, particularly their water holding capacity. The soils (Table 2.1) of the regions are generally acidic with very low organic matter content.

Table 2.1: Fertility status of soils in Northern Ghana

Region	pH	% Organic Matter	% Total Nitrogen	Available Phosphorus (mg/kg soil)	Available Calcium (mg/kg soil)
Northern	4.5 – 6.9	0.6 -2.0	0.02 – 0.05	2.5 – 10.0	50 – 90
Upper East	5.1 – 6.8	1.1 – 2.5	0.06 – 0.14	0.8 – 144	14 – 470
Upper West	6.0 – 6.8	0.5 – 1.3	0.01 – 0.07	2.0- 7.4	52 – 151.5

Source: SRID (2010)

According to SARI (1994), about 60% (and up to 97% in the Upper East Region) of farmers in Northern Ghana grow Pearl millet in what has been described by Diehl *et al*. (1985), as a millet-based farming system. The system consists of Millet intercropped with sorghum, maize, cowpea, or groundnut. According to Policy Planning Monitoring and Evaluation Division of the Ministry of Food and Agriculture (PPMED, 1991), in 1990 an estimated 244,000 ha of land put to millet production yielded 80,000 tonnes of grain. In 2010 (20 years later), the actual cropped area declined to 177,000 ha but grain yields increased to 219,000 tonnes (SRID 2011). This increase in yield could be attributed to prudent and efficient management practices adopted by farmers and not as a result of farmers using improved seed.

2.9 Conservation of landrace of Pearl millet

Conservation of Pearl millet seeks to develop methods and measures to better manage existing landraces for the sustainable intensification of agricultural production, especially in its areas of production where it is currently under threat of extinction (Bennett-Lartey and Oteng-Yeboah, 2008). This is important because they serve as source of trait supply for crop improvement and climate change adaptation. There has been several method propounded by many people for the conservation of Pearl millet. A typical scheme (Fig. 2.5) has been proposed (GCDT, 2012) and is being used worldwide. Under this scheme, farmers are found at the base of the pyramid while the conservation is at the top. All other players are found within these two extremes and are necessary stakeholders in the system. Characterisation often links conserved germplasm to utilization with farmers as the key stakeholder or beneficiaries.

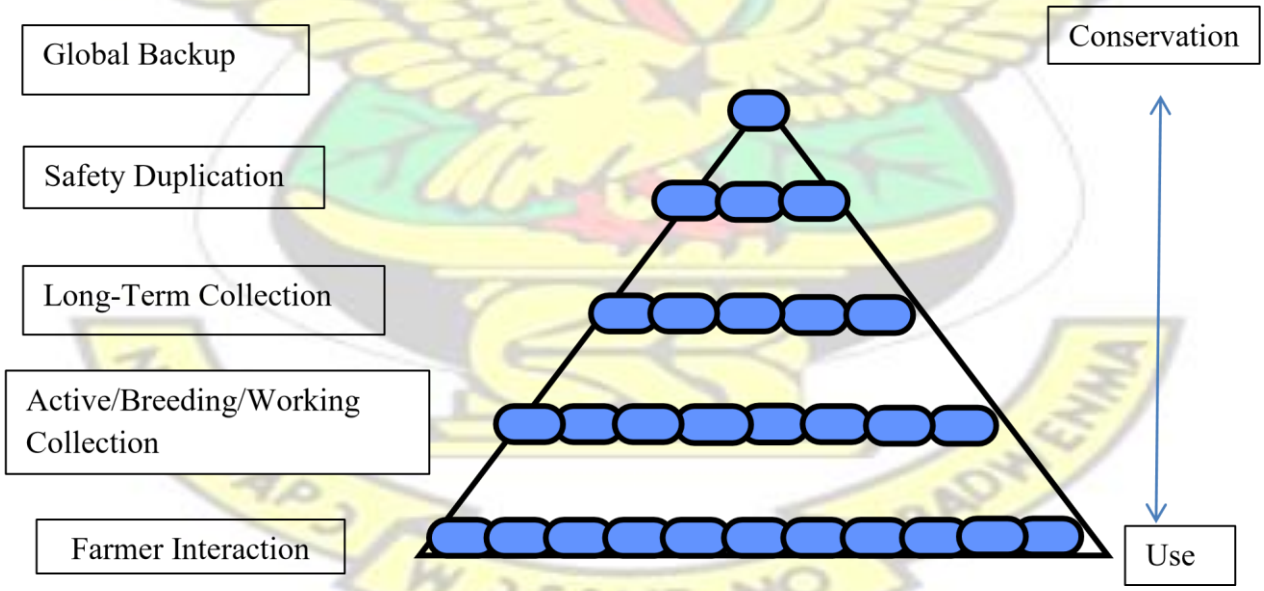

Figure. 2.4 Scheme of global seed use and conservation system

= Institutions

Concept Source: Sackville Hamilton R. (GCDT. 2012)

The conserved germplasm need to be evaluated and characterised (Brown, 1983; Khairwal *et al*., 2007) in other to identify unique genotypes that could be used by breeders for crop improvement work. In Ghana the crop is conserved (stored in Barn) on year-to-year basis. Farmer would normally use seed selected from the previous season for the current season. Thus the life span of every conserved seed lot is one year (one season). Under improved conservation systems however, Pearl millet can be stored for between 5 and 30 years (GCDT, 2012) before any regeneration is carried out. This form of conservation could be done as short term (1 -5 years), medium (5 -10 years) or long term (above 15 years at -18º to -20ºC) bases.

Bennett-Lartey and Oteng-Yeboah (2008) lamented the wide spread genetic erosion of plant species in Ghana due to extensive land use and land use change. They observed that replacement of local varieties, land clearing, pests, weeds, diseases, population pressure, and changing agricultural systems are the most striking factors causing plant genetic erosion. Between 1996 and 2005 germplasm of various crops were collected, in Ghana, under various research programmes including National Agricultural Research Project (NARP), Root and Tuber Improvement Project (RTIP), Agricultural Sub Sector Investment Project (AgSSIP), and Cashew Development Project. According t o Bennett-Lartey and OtengYeboah (2008), a total of 10,000 accessions of germplasm, including Pearl millet, have so far been collected and conserved (complementary *in situ* and *ex situ* conservation) at PGRRI under the improved system of conservation.

2.10 Concept of core collection and its relevance

Core collections are a full representative of the diversity of an entire collection and consist of a limited set of accessions taken from that entire collection as a representative of the genetic spectrum in that collection (Brown, 1989). The concept is an efficient approach to enhancing

the use of germplasm in crop improvement. ICRISAT genebank is currently holding a core collection of 2,094 accessions (from an entire collection of 20,766 accessions) of Pearl millet worldwide (GCDT, 2012). With reduced core collections it becomes very easy to do characterisation and evaluation even though with the current number at ICRISAT, this work can be tedious or not feasible (GCDT, 2012). A mini-core collection concept is now being adopted to further reduce the numbers to manageable levels without having to compromise representative of the entire diversity in the population (GCDT, 2012). This concept has been used by ICRISAT to reduce the current 2094 accessions to 238 mini-core collections using 18 morpho-agronomic traits.

2.11 Germplasm characterisation

For effective and efficient utilisation of any collected germplasm, it has to be systematically characterised and possibly evaluated for many of their traits. This requires a lot of human and financial resources. It is reported (GCDT, 2012) that all the accessions at the genebank of ICRISAT have been characterised and evaluated for 23 morpho-agronomic characters following the descriptors for Pearl millet (IBPGR and ICRISAT, 1993). This thus makes available some information that could readily be accessed for trait development and enhancement.

2.12 Application of DNA marker techniques in Pearl millet characterisation

Various selection and breeding techniques as well as their modifications genetic diversity study have been used in Pearl millet varietal (inbred lines and hybrids) development. The genetic diversity of a population can be determined using morphological and molecular markers. Phenotypic traits are less relied upon because they are frequently affected by environmental

factors as well as developmental status of the plant (Tatineni *et al.*, 1996). Globally, crop improvement researchers are resorting to the use of molecular markers as an effective and appropriate tool for basic and applied studies in general biological agricultural production systems (Jones *et al*., 1997) including Pearl millet breeding work.

This has become necessary due to the weaknesses in morphological data resulting from environmental influences on quantitative traits. Molecular markers are not influenced by the environment and are therefore more efficient tools that are employed on plant breeding work.

DNA marker techniques such as Restriction Fragment Length Polymorphism (RFLP), Random Amplified Polymorphic DNA (RAPD), Amplified Fragment Length Polymorphism (AFLP), Simple Sequence Repeats (SSRs/microsatellites), Expressed Sequence Tag (EST), and Single Nucleotide Polymorphism (SNP) are now being used for diversity analysis, linkage mapping, and Marker-Assisted Selection (MAS) in Pearl millet (Zerihun, 2009; Heng-Sheng *et al*., 2012; Ranjana, 2009 and Senthilvel *et al*., 2008). Marker techniques have been used to assess genetic diversity at the molecular level in germplasm collections, thus assisting in making reasonable choices of hybrid parents, studying population structure, mapping and tagging genes/QTLs (quantitative trait loci) for agronomic traits and disease resistance (ICRISAT, 2005).

Bjorklund *et al*. (2009) maintain that Molecular markers are often used for investigating genetic diversity due to their high efficiency, low sample number requirements, and low number of limitations on the growth stage. Gulia *et al*. (2007) reported extensive work done by many authors using molecular marker technique to genetically map downy mildew, drought tolerance and grain yield, and for characters involved in domestication of Pearl millet. Several other examples abound in Foxtail millet using markers such as RFLP, AFLP and RAPD with a lot of success. Zerihun (2009) reported that though molecular marker technique was a laudable idea,

its application and choice of marker should be guided by factors such as reliability, quantity and quality of DNA required, technical procedure for marker assay, level of polymorphism and cost. At the peasant farmer level however, most of the selection criteria is based on physical (Phenology) appearance of the plants as they grow on the field.

2.12.1 The Microsatellites/Simple Sequence Repeats (SSR) markers and their usefulness

Heng-Sheng *et al.* (2012), define Microsatellites also known as Simple Sequence Repeats (SSRs), as a tandem repeating sequence of 1-6 base pairs of DNA. But Budak *et al*. (2003), describe SSRs as consisting of 2 to 5 nucleotide sequences such as $(GA)_n$, $(ATT)_n$ or $(ATGT)_n$ that are tandemly repeated with highly conserved flanking sequences and are ubiquitous in eukaryotic genomes and thus provide the basis for Primer design and use in a Polymerase Chain Reaction (PCR)-based marker amplification strategy.

As reported by Gupta *et al.* (1996), Kumar *et al*. (2009) and Shahroodian *et al.* (2011), SSRs Markers have been useful for their high number of polymorphisms, high level of variation, abundant information and ease of manipulation with universal primers as such are widely employed in many species. Their use enables one to discriminate between homo- and heterozygous state, and increases the efficiency of genetic mapping and population genetic studies (Haussmann *et al.,* 2000). Pearl millet, being an out-crossing species, can be best studied using such SSRs markers to explore the unique gene diversity that is likely to occur through recombination of genes during fertilisation.

Of all the DNA marker techniques available, Microsatellites have proven to provide good information relating to study of genetic relationship among closely related plant species. This is because of their exceptionally high level of polymorphism (Bowcock *et al*., 1994). Hernandez *et al.* (2002) reported that microsatellites exhibit co-dominant inheritance and their detection can readily be automated. Simple sequence repeats serve as a tool for the

identification of genotypes, tagging of important traits, and in population genetic studies (Gupta and Varshney, 2000). Budak *et al*. (2003) also reported that GA/CT repeats are abundant and easily detected in Pearl millet when SSRs are used.

ICRISAT (2005) reports indicates that there were 500 homologous RFLP and 140 SSR markers available for peal millet. The report however admitted that there were very limited uses of the RFLP markers because it was thought to be a very slow system and when they were converted to PCR-based markers, they still failed to detect polymorphism that could be scored reliably on gels. In the recent past there has been discovery of microsatellites in Expressed Sequence Tags (ESTs) leading to the development of EST- SSRs by electronic search of EST data bases (Senthilvel *et al*., 2008). As a PCR-based approach, this technique can be used to design 18 – 20 base pair primers that provide a unique sequence _tagging' of the gene to detect a unique express region of the genome (Hernandez *et al.*, 2002). Even though EST-SSRs constitute a novel source of markers that are physically associated with coding regions of the genome (Senthilvel *et al*., 2008) and are easily transferable to closely related species (Holton *et al*., 2002 and Wang *et al*., 2005), its exploration is limited to the species for which EST sequence information is available (Senthilvel *et al*., 2008).

Molecular work in Pearl millet is therefore able to take advantage of the several proven techniques available in identifying diversity and improving on landraces to obtain better varieties and hybrids to feed the ever-increasing rural population in the semi-arid regions of West Africa and Ghana in particular.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Items used in germplasm collection

Prepared data sheets, envelopes, stapler and pins, writing pad, marker pens, camera, and a map of Ghana were used in the collection process. The data sheets (Appendix I) captured very important ethno-botanical information, cultivation and management practices as well as location/community, ethnic group, local name, uses and problems associated with it. Seed or panicle samples were put in well-labelled (collection number, Name of donor, village/region) envelope using the permanent marker pen.

3.2 Collection mission and coverage

Pearl millet in Ghana is grown in the three regions of the North namely, Upper West, Upper East and Northern regions. The collections therefore targeted these Regions. The collection was done in May/June. At this time most farmers had either started planting or were preparing their material for planting and hence were more willing to release small quantities for us. Seed samples (threshed and/or panicle forms) were taken between 20 – 45km intervals along predetermined routes using the physical Map of Ghana. This was also done such that there were at least one and at most three samples collected in each administrative district of the regions. Forests areas were also considered in determining the distance within which to collect samples.

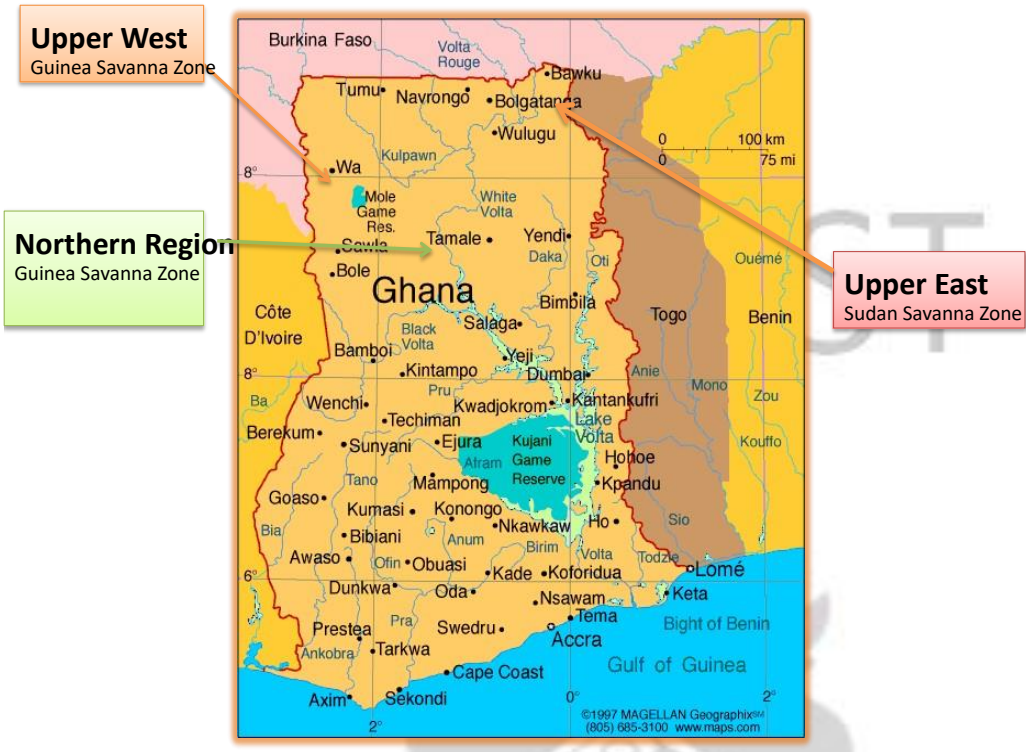

Figure 3.1: Regions where collection was made

All the collected samples were picked from homes in head (panicle) form or threshed seed that was ready for planting by the donors. It was important that market places be avoided during the collection in order to minimise mixed seeds that may have been gathered from different farmers or homes. Collections at homes did not include purchased seed. In all cases, collection were said to have been seed preserved from the 2010 cropping season, within one year of harvest storage. Post collection operations such as threshing and cleaning were done at the Manga Agricultural Research Station of CSIR-SARI (Latitude 11° - 01‘ N and Longitude 00 ° -16 ° W with and elevation of 249m above sea level).

3.3. Morpho-agronomic characterisation

This involved soil sampling, land preparation, planting, and field maintenance and data collection.

3.3.1 Soil physical and chemical properties of the characterisation field at Manga

Soil samples, taken at a depth of 0-30cm (W-Pathway), at the characterisation site were analysed for the determination of their physical and chemical properties at the CSIR-SARI soil laboratory. Data on physical properties (particle size distribution) comprising Sand-siltclay percentages was used to describe the texture of the soil. Soil chemical data obtained on pH (1:2.5 soil-water ratio) using digital pH-meter, Organic C (%) by Walkley-Black wet oxidation method (Nelson and Sommers, 1982), total N (%) by Kjeldahl procedure (Bremner and Mulvaney, 1982), exchangeable base levels (m.e. /100 g soil), exchangeable acidity and availability of P and K (ppm) by Bray 1 method (Oslen and Sommers, 1982), were used to describe soil nutrient status.

3.3.2 Field establishment

All the accessions collected were prepared through threshing of the panicles, cleaning, and repackaging before planting. One hundred and twenty-six accessions (Appendix II) were prepared and planted at the Manga outstation of CSIR-SARI, located in Bawku in the Upper East Region, Ghana, following the on-set of rains in June. The field was prepared with a tractor-mounted harrow whiles ridges made using bullocks at an approximately 0.75m interval. Each material was planted on a two-row plot at a planting distance of 0.75m X 0.3m and row length of 3m (approximately 20 stands per plot). Each material was replicated four times (with 1m distance between replicates) to avoid complete loss of any material or information through any

unforeseen incidences. A maximum of three seeds hole^{-1} and the seedlings thinned to one plant two weeks after emergence. Three of the accessions from Northern Region were not viable hence did not germinate. A single dose of NPK (15-15-15) fertiliser was applied at the rate of 75kg/ha (12.66g per plot) 25 days after emergence and at first weeding. A second weeding was done at forty-five days after emergence and final reshaping carried out 15 days later. The reshaping was to give support to the plants against lodging during stormy rains and to conserve moisture at the root level of plants as well as enhancing drainage after rains.

3.3.3 Traits measurements

The standard millet descriptor (IBPGR and ICRISAT, 1993) was used as a guide to take data. The selected data included the following:

i. Total plants count per plot based on one plant per stand ii. Total number of plants with Downy mildew (DM) at 30 Days after sowing (DAS) on whole plot bases iii. Total number of plants with Downy mildew (DM) at dough stage (DAS) on whole plot bases iv. Number of days from sowing to when 50% of the plants within a plot have boots

v. Average number of tillers per plant based on average of 10 plants per plot selected at random

vi. Average number of productive tillers (tillers with grain-filled heads) per plant based on average of 10 plants per plot selected at random vii. Average plant height at dough stage (cm) based on average of 10 plants per plot and measured from the soil level to the tip of the head

viii. Fresh stover weight per plot (kg) at harvest and converted to per plant bases ix. Average panicle/spike/head length (cm), measured from the base to the tip of the head, based on average of 10 heads per plot

x. Average panicle/spike/head girth (cm), measured from the broadest portion of the head, based on average of 10 heads per plot xi. Average 1000 seed weight (g) based on average of four samples per plot xii. Panicle/spike/head shape of each accession using the millet descriptor xiii. Panicle/spike/head density of each accession using the millet descriptor xiv. Seed colour using the standard millet descriptor xv. Seed shape using the standard millet descriptor

DM incidence per cent was then calculated using the DM counts

3.3.4 Maintenance of seed purity

In order to maintain purity of each accession, heads (at least five heads each) were crossed using the full-sib method. At harvest these were bulked as seed stock for each accession for duplicate storage for future use.

3.4. Molecular Characterisation

3.4.1 Seedling establishment

For each accession (from the full-sib lot), about fifty seeds were picked and placed in well labelled seed envelopes. These were then established in a nursery at CSIR-CRI plant house at Fumesua, Kumasi for two weeks. Fresh growing leaves were picked and prepared for Total DNA extraction at the CSIR-CRI biotechnology laboratory, Fumesua, Kumasi.

3.4.2. DNA extraction

The total DNA was extracted from the leaves using the sweetpotato extraction method/procedure (steps) described below:

200mg of leaf tissue was weighed into 2ml eppendorf tube and grind to find powder with liquid nitrogen. 800µl of Buffer A (lysis powder) was then added and Incubated at 90°C for 10min and vortex done every 5min after which the suspension was allowed to cool at room temperature for 2min. 400µl 5M potassium acetate was then added and gently mixed by inversion six times before incubation in ice for 30min with shaking. The suspension was then Centrifuge at 13, 000 rpm for 10min and the upper phase transferred to a new eppendorf tube and 1 volume of cold isopropanol, 1/10th of 3M sodium acetate added and mixed 10X by inverting and further incubated at - 20°C for 1 h, and centrifuged at 13, 000 rpm for 10min for pellet formation. The supernatant was poured off and pellets washed with 800µl, 80% ethanol and Centrifuged at 14, 000 rpm for 5min before drying at room temperature. 500µl 1X TE Buffer was added to dissolve pellets in eppendorf tube and 4µl RNase A added and incubated at 37°C for 30min and 250µl of 7.5M ammonium acetate added and incubated on ice for 3min before it was centrifuged at 13, 000 rpm for 5min. The supernatant was then transferred into a new 1.5ml tube and 700µl of isopropanol added and mixed by inversion (ice inversion) and centrifuged again at 13, 000 rpm for another 15min. The pellets were washed with 1ml 80% ethanol after the supernatant was discarded and centrifuged at 14, 000 rpm for 5min after which the DNA pellets were dried at room temperature. The DNA quality was checked by dissolving pellets in 200µl 1X TE Buffer and running on 0.8% agarose gel

3.4.3 Genotyping with primers

3.4.3.1 Type and number of primers used

A total of 36 known Pearl millet SSR primers (Appendix III) were used to run the Polymerase-Chain Reactions (PCRs) on 119 accessions. DNA of four accessions were of poor quality and hence could not be used to run the PCRs.

3.4.3.2 PCR and Electrophoresis

The protocol used as described below was one developed by Tegelstrom (1992). PCRs were carried out in a 10 µl reaction mixture containing 10–15 g of genomic DNA, 2 pmol of each primer, 1mM $MgCl_2$, 0.1 mM of each dNTP, 1× reaction buffer, and 0.2 U *Taq* polymerase (Bioline). After one denaturing step of 3 min at 94°C, a touchdown amplification program was performed on GeneAmp 9700 thermal cycler (Applied Biosystems, USA). This profile consisted of a denaturing step of 25 sec at 94°C and an extension step of 30 sec at 72°C. The initial annealing step was 20 sec at 64°C for one cycle and subsequently the temperature was reduced by 1°C for every cycle until a final temperature of 55°C was reached. The annealing temperature of 55°C was maintained for the last 35 cycles of amplification, followed by final extension of 72°C for 7 min. PCR products were size-separated on native polyacrylamide gels (6%) run on 0.5× TBE buffer at 600 V for 3 hours using a Bio- Rad® sequencing gel apparatus. After electrophoresis, the banding patterns of PCR product on PAGE gels were visualized by silver-staining

3.5. Data analysis

GenStat Discovery Free Edition 4 was employed for the analysis of variance (ANOVA) and means from the agro-morphological data were separated at 5% confidence level. Mean days to 50% booting was then used to group all accessions into three distinct maturity groupings. Molecular (genotyping) data was subjected to analysis using Power marker version 3.25 (Paul and Demitri, 2012) to generate Polymorphic Information Content (PIC), Gene diversity (Expected Heterozygosity – He) and Observed Heterozygosity (Ho). SAHN (Sequential Agglomerative Hierarchical Nested) clustering based on UPGMA (Unweighted Pair-Group Method with the Arithmetic Means) was employed to group the accessions (based on the morphological data collected) into distinct tree clusters from which core representatives per cluster were picked.

The Polymorphism Information Content expressed as $(PIC_i) = 1 - \sum_{u=1}^{K} \boldsymbol{P}lu^2 - \sum_{u=1}^{k-1} \sum_{v=u+1}^{k} 2\, \boldsymbol{P}lu^2\, \boldsymbol{P}lv^2$

the Expected Heterozygosity as (HExp): $= (1 - \sum_{u=1}^{k} \boldsymbol{P}lu^2) / \{1 - (1 + f)/n\}$, and the

Observed Heterozygosity as (Hobs): $= 1 - \sum_{u=1}^{k} \boldsymbol{P}luu$

where; ***P****lu or* ***P****u: Allele population frequency* ***P****uv or* ***P****luv: Genotype population frequency*

f: Inbreeding coefficient

CHAPTER FOUR

RESULTS

4.1: Environmental conditions at the characterisation site at Manga Research Station

The field work was conducted at the Manga Agricultural Research Station of SARI in Bawku located between Latitude 11° - 01‘ N and Longitude 00 ° -16 ° W with and elevation of 249m above sea level in the Upper East region. In addition to mean temperatures and rainfall (Table 4.2) conditions over the period soil data were collected and are presented table 4.1.

4.1.1: Soil characterisation

Analysis of soil samples taken at the site revealed that the soil was generally loamy sand with percentage sand, silt and clay (0 - 30 cm depth) being 80.3%, 14.88% and 4.82% respectively as shown in Table 4.1. The soil was acidic (pH 4.88) with percentage organic Carbon being 0.62 while total Nitrogen (%), available phosphorus (mg kg-1) and exchangeable Potassium (cmol (+) kg-1) were respectively 0.06, 11.98 and 49.5.

Table 4.1 Some Physical and Chemical Properties of the surface (0-30 cm) soil at the characterisation site at the Manga Agricultural Research Station, 2011.

Soil properties	Quantity/Description
Sand (%)	80.3
Silt (%)	14.88
Clay (%)	4.82
Soil texture	Loamy sand
Soil pH (H_20)	4.88
Organic carbon (%)	0.62
Total nitrogen (%)	0.06
Available P (mg kg^{-1})	11.98
Exchangeable cations cmol (+) kg^{-1})	
Ca	0.95
Mg	0.4
K	49.5
CEC [cmol (+) kg^{-1}]	2.28

Analysis done at CSIR-SARI soil laboratory

4.1.2: Rainfall and temperature trends

Annual rainfall amounts have been irregular over the years as is depicted in Table 4.2. The data indicates that the year 2011recorded an amount of 686mm which was less than 1091mm of 2010 and the ten-year average (1054.2mm). This result also reveals that the season is becoming shorter. This is because the ten-year trend has only two months recording zero rainfall whereas in the recent past (2010 and 2011) the number of dry months has increased to five; a clear case of climate change effect. August is the wettest month of the year recording values higher than 250mm with the other wet months having values less than 200mm during
2010 and 2011.

The trend in temperature changes, as observed from Table 4.2, is not very much different. The years have had fairly constant temperatures with the mean around 29.2ºC (2011) and 29.4ºC (2010). Temperature is observed to rise above the 30ºC mark during the period February through to May.

Table 4.2: Monthly precipitation and mean temperatures for 2010, 2011 as well as a tenyear cumulative average for the weather station at the Manga Research Station

Month	Rainfall			Mean temperature		
	2010	2011	1999-2008 (Average)	2010	2011	1999-2008 (Average)
January	0.0	0.0	0.0	27.9	27.4	27.5
February	0.0	0.0	1.2	31.5	30.1	29.9
March	0.0	0.0	1.9	33.4	34	33.5
April	13.5	12.7	22.7	33.4	32.1	32.5
May	114.6	79.1	109.1	31.5	30.7	31.2
June	130.7	132.1	143.9	28.4	28.8	28.6
July	198.3	92.3	254.9	27.2	29	27.4
August	357.8	253.2	295.7	28.3	26.7	26.9
September	149.6	71.2	173.3	27.1	27.8	27.1
October	126.5	45.4	51.4	28.1	29	28.7
November	0.0	0.0	0.1	28.8	29.3	29.1
December	0.0	0.0	0.0	27.1	25.3	28.7
Total	**1091**	**686**	**1054.1**	**352.7**	**350.2**	**351.1**
Annual Average	**90.9**	**57.2**	**87.9**	**29.4**	**29.2**	**29.3**

Source: Weather station of CSIR-SARI, Bawku

4.2: Millet accessions/Landraces collected

A total of 126 (Table 4.3 and Appendix II) accessions/landraces were collected across the entire Pearl millet production regions of Ghana. Northern Region had the largest number of collections of 56 accessions/landraces (representing 44.4 %) due to the land size (21 %: Fig. 2.3) which was far more than 44 (34.9 %) from Upper East Region and 26 (20.6 %) from Upper West region.

Table 4.3 Total number of Pearl millet accessions collected by Regions

Region	Total number of collections		
	Early maturing	Late maturing	Total
Upper East	21	23	44
Upper West	0	26	26
Northern	6	50	56
Total	27	99	126

The information as captured on the data sheet show that the accessions collected were made up of two main maturity groups namely early (27) and late (99). While Upper West did not record any early maturing group, Upper East recorded the highest number of 21 with Northern region contributing only six from this group (Table 4.3).

4.3: Morpho-agronomic characterisation

Of the total collections of 126, three accessions (SARMIL 055, 075 & 081: all from northern region) did not germinate during the characterisation and hence no morphological data could be generated on them. Days to fifty per cent booting (DFB) classified the accessions into three

distinct classes as shown in Table 4.4. These were early maturing (37 – 59 days), medium maturing (60 – 100 days) and late maturing (above 100 days). Majority (54) were in the medium maturing group followed by late maturing group with 45 collection and 24 constituting early maturing group. Upper West Region had no early maturity group but Upper East and Northern Regions had 21 and three respectively.

With respect to medium maturing group, Upper West and Northern Regions contributed 17 collections each (63% of that group) with Upper East contributing 20 collections. Whereas more early (87.5 %) and medium (37.0 %) maturing Pearl millet is grown in the Upper East Region, Upper West and Northern Regions are home to the late-maturing group of Pearl millet as they contributed 93.3 % (with Northern Region alone contributing 73.3 %) of that group and 31.5 % each of the medium maturing group.

Table 4.4 Regional distribution of the millet accessions based on days to 50 % booting

Region	Total collected	Maturity group (Da to 50 % Booting)		
		Early (37-59)	Medium (60-100)	Late (101+)
Upper East	44	21	20	3
Upper West	26	0	17	9
Northern	56 (-3)*	3	17	33
Total	126 (-3)	24	54	45

(-3)* are those that failed to germinate during field establishment at Manga

4.3.1 Qualitative trait variation within the accessions

Characteristically the Head type as revealed by the collection and presented in Figure.4.1 was made of only two densities or compactness, thus semi-compact (101) and loose (22) as well as two head shapes namely cylindrical (110) and candle (13) shapes. The trend was similar for the various maturity groups. The predominant head density was semi-compact for all the maturity groups (70.88%, 85.19% & 84.44% for early, medium and late groups respectively) whiles cylindrical head shape was also common among the groups (91.7%, 85.2% & 93.3% respectively for early, medium and late groups).

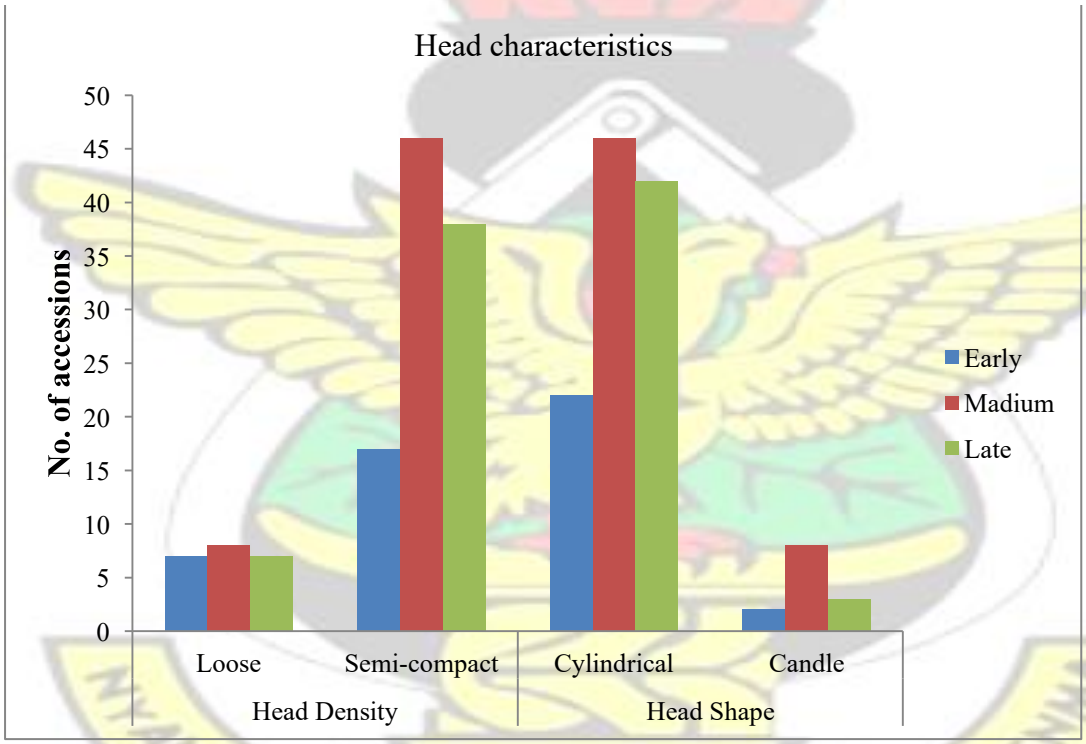

Figure 4.1: Qualitative characteristics of head density and shape distribution of 123 accessions

Basically the entire collection showed five main seed colours such as Ivory, yellow, grey, deep-grey and grey-brown seed colours (Fig. 4.2) based on Royal Horticultural Society (RHS) colour codes. Deep grey constituting 42.3 % and Grey constituting 38.2% were the dominant seed colours.

Whereas the early maturing group had deep-grey as its dominant colour followed by greybrown, the late maturing group showed the reverse of what pertains to the early maturing group (Figure. 4.2). Again the dominant colour for the medium group was grey followed by deep-grey. Furthermore, early maturing group did not have ivory and yellow seed colours. Similarly, medium and late maturing groups did not show grey-brown colour.

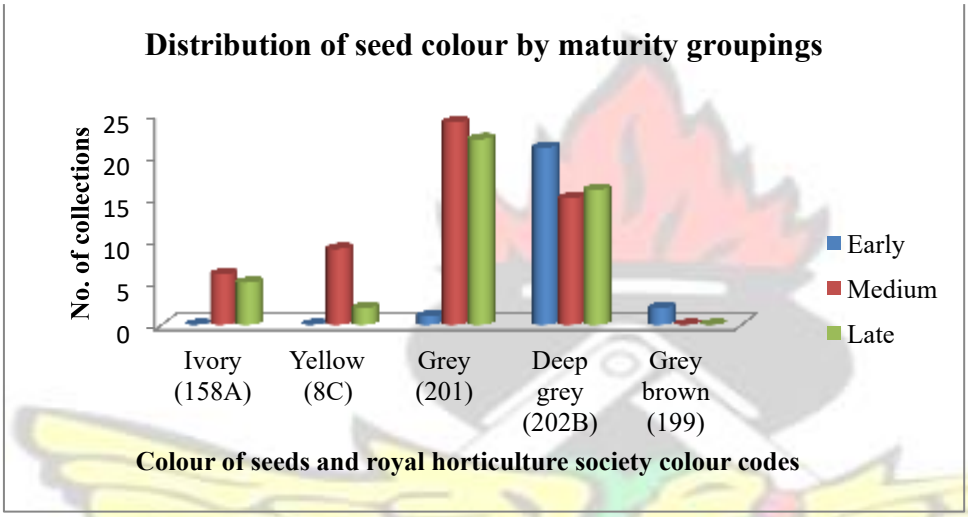

Figure 4.2: Colour distribution of 123 accessions collected from the regions

The entire collection revealed basically three seed shapes (Figure.4.3) namely obovate (16.0%), hexagonal (24.0%) and globular (60.0%). The trend in terms of prominence was similar for individual maturity groups except for the early group where obovate showed higher percentage (25.0%) than hexagonal (16.7%)

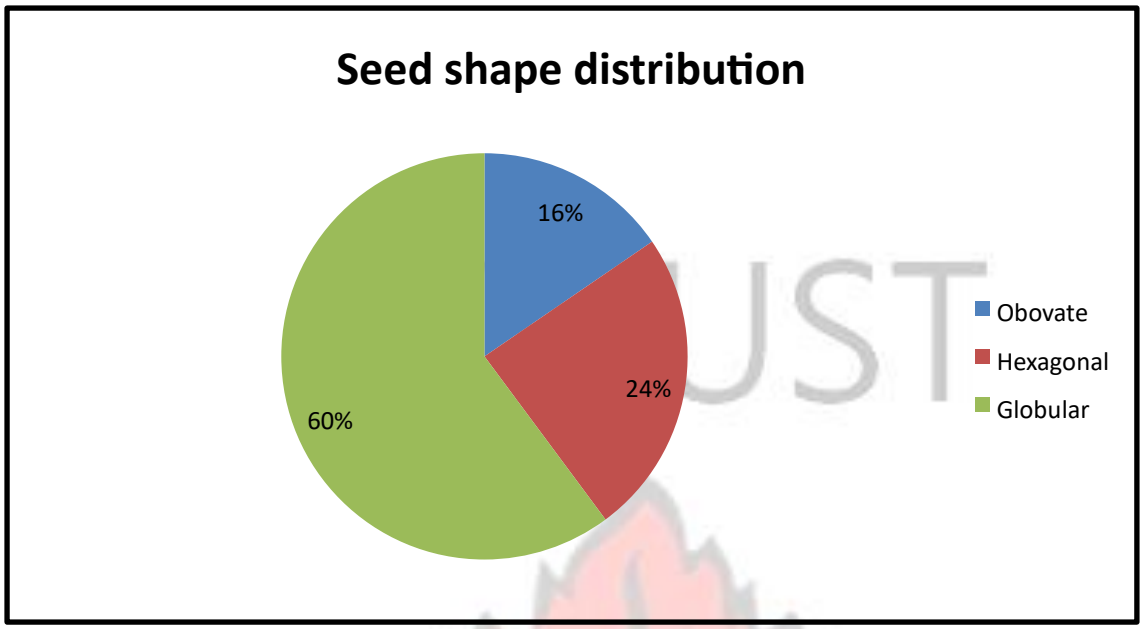

Figure 4.3: Seed shapes of 123 accessions collected from the regions

4.3.2 Quantitative trait analysis of the millet accessions using ANOVA

Results on days to 50% booting (Table 4.4) were used to group the entire collection into three main maturity groups. The morpho-agronomic as well as genotyping data are therefore presented and discussed as such, except otherwise indicated

4.3.2.1 Analysis of Variance (ANOVA) for the early-maturing group

Downy mildew incidence at dough stage, averaged plant height, head girth and length as well as plant stand plot^{-1} of the early-maturing group showed significant statistical variation among the accessions (Table 4.5).

Plant stand, which is a reflection of seed viability, ranged from 4.5 (SARMIL 083) to 20 (SARMIL 104) with a mean of 16.07 plants (Appendix IV-D). Apart from SARMIL 083, all the other accessions had DM values above 12. The mean at dough stage rose to 39.60%.

Whiles at 30 days after planting the incidence spanned from zero for SARMIL 083 and SARMIL 125 to 29.20% for SARMIL 089, it shot up to between 11.90% (SARMIL 102) and 63% (SARMIL 089) with a mean of 39.60% by the time the crop reached dough stage (Appendix IV-D). SARMIL 089 was consistently the most infected accession and, together with SARMIL 088, SARMIL 096 and SARMIL 097, recorded infection above 50% at dough stage of the crop. Eleven accessions recorded resistance (DM below 10%) at 30 days after planting but by dough stage the resistance was lost.

The average head length was 18.3cm while average girth was 8.4cm. SARMIL 097 and SARMIL 111 produced the longest and shortest heads (24.67cm and 15.3cm respectively). With the exception of SARMIL 097, SARMIL 100, SARMIL 102, SARMIL 107, SARMIL 109 and SARMIL 125, which were shown to be significantly different from SARMIL 111 relative to head length, the rest did not vary. Again while SARMIL 097, SARMIL 100, SARMIL107, SARMIL 109 and SARMIL 125 produced head with lengths slightly below 25cm, the rest of the accessions produced head lengths below 20cm. The results also showed that the head length of SARMIL 097 was not statistically different from SARMIL 107, SARMIL109 and SARMIL 125 even though they all produced head above 20cm.

Average head girth even though significantly variable among these accessions, was below 10cm (Appendix IV-D, Table 4.5). SARMIL 092 and SARMIL 113 were the only ones with girths above 9.0cm. There was none with girth below 7.5cm (Appendix IV-D). The average plant height for the early-maturity group was 159.8cm with variations from 141.5cm (SARMIL 079 and SARMIL 092) to 175.8cm (SARMIL 085). Fifty per cent of these accessions showed varying levels of significant difference in plant height to SARMIL 079 and SARMIL 092 but not among themselves.

Days to 50% booting, stover yield plant^{-1}, thousand seed weight, total tillers and productive tillers were all not significantly different between accessions of the early-maturity group. However, the earliest maturing accession (37 days to 50% booting) was SARMIL 077 while the latest was SARMIL 096 (45 days booting). Whereas SARMIL 076 produced the least stover weight plant^{-1} (0.18kg), SARMIL 092 was the highest yielder for stover (0.56kg). Also thousand seed weight ranged from 8.88g to 12.21g. Thirteen accessions had average 1000 grain weight above 10g (Appendix IV-A). Up to eight (average being six) tillers were counted per plant but just about four produced heads as shown in Appendix IV-D.

Table 4.5: ANOVA (Mean squares) for selected agronomic traits of the early-maturing group at Manga

Source of variation	df	DM @ 30 days	DM @ maturity	Average head girth	Average head length	Average plant Height	Stover yield	1000 seed weight	Average total tillers	Average prod've tillers	DFF	Plant stand/plot
Replication	3	757.8	7877	5.2752	108.602	2212.1	0.83155	42.419	0.021	0.113	2.083	191.7
Accession	23	159.9NS	668.0**	1.1439**	23.997**	358.9**	0.0280NS	3.539NS	1.458NS	1.746NS	6.551NS	42.51**
Error	69	186.1	230.3	0.5211	8.547	179.9	0.0217	4.188	0.32	1.08	7.04	12.95
Total	95	95	95	95	95	95	95	95	95	95	95	95

** Significant at 1%, NS: Not Significant; DM = Downy mildew, DFF=Days to 50% flowering, df= Degree of freedom, prod‘ve = productive

4.3.2.2 Analysis of variance (ANOVA) of the medium-maturing group

Days to 50% booting, (DFB), average head length and girth, and average plant height were highly significant ($P<0.05$) among the medium-maturing accessions whiles seed weight showed significance at $P<0.05$ (Table 4.6). Accession SARMIL 070 took 100 days to reach DFB while accession SARMIL 091 was the earliest among the group members, attaining DFB at 68 days (Appendix IV-B). SARMIL 070 was however not significantly different from 19 other accessions within this group.

Downy mildew, the main disease of Pearl millet, showed an increasing trend with time. At 30 days after planting downy mildew (grand mean of 11.30%) did not show any significant difference among the accessions but at dough stage it was highly significant even at p(0.01) and varied among the accessions. The rest of the 33 accession indicated various levels of variation among themselves. On the average medium- maturing group took 84.81day to DFB with 22 (41.50%) accessions having figures above this average as shown in Appendix IV-D.

The variability in head length and girth among the accessions were extensive spanning all regions and districts. For instance, head length ranged from 18.2cm for SARMIL 044 to 29.45cm for SARMIL 003 with a mean of 23.83cm whiles that of head girth ranged from 6.40cm for SARMIL 002 to 11.93cm for SARMIL 082 with a mean of 8.40cm (Appendix IV-D). The data revealed five accessions (SARMILL 044, SARMIL 053, SARMIL 063, SARMIL 067 and SARMIL 070) having head lengths less than 20.0cm and as many as 17 accessions recording head girths below 8.0cm (Appendix IV-B). Again the results, as shown in table 4.6, did not show any statistical difference in girth between SARMIL 015, SARMIL 043, SARMIL 045, SARMIL 065, SARMIL 068, SARMIL 087, SARMIL 091, SARMIL 103, SARMIL 112 and SARMIL 121. However, SARMIL 082 was observed to be statistically broader (11.93cm girth) than the rest of the 52 accessions.

Plant height (cm) was observed to vary significantly (P<0.001) and ranged between 276.2cm (SARMIL 093) to 394.5cm (SARMIL 010) with grand mean value of 341.3cm (Table 4.6 and Appendix IV-D). All accessions, except SARMIL 090 and SARMIL 093, recorded plant heights above 300cm. Seed weight, a factor of seed boldness, varied (P=0.021) among the accessions. 17 accessions had 1000 seed weight above 10.00g with SARMIL 080 recording the highest weight of 12.07g (Appendix IV-B).

Average plants stand plot^{-1}, downy mildew (30 days & dough stage), stover yield as well as total and productive tillers did not reveal any significant difference for the medium-maturing group (Table 4.6). However, just as observed with the early-maturing group, mean downy mildew incidence increased (Appendix IV-D) as the plants advanced in age on the field (7.47 to 23.90%). On the average, this maturity group produced 7.43 and 5.22 total and productive tillers, respectively.

Table 4.6: ANOVA (Mean squares) for selected agronomic traits of the medium-maturing group at Manga

Source of variation	df	DM at 30 days	DM at maturity	Average head girth	Average head length	Average plant Height	Stover yield	1000 seed weight	Average total tillers	Average prod've tillers	DFF	Plant stand/plot
Rep	3	955.4	44.7	12.63	206.59	22634	14.527	63.015	7.259	6.259	27.00	205.86
Accession	53	101.4NS	408.9NS	3.591**	32.65**	2183**	0.267NS	6.303*	3.159NS	1.975NS	140.82**	18.87NS
Error	159	114.8	327.7	1.05	14.16	1100	0.231	4.08	2.599	1.806	33.21	17.63
Total	215	215	215	215	215	215	215	215	215	215	215	215

** Significant at 1%, NS: Not Significant; DM = Downy mildew, DFF=Days to 50% flowering, df= Degree of freedom, prod‘ve = productive

4.3.2.3 Analysis of variance (ANOVA) of the late-maturing group

Average head length (cm), plant height (cm), 1000 seed weight (g), total tillers plant^{-1} and plants plot^{-1} of the late-maturing group all showed highly significant ($P<0.01$) variations amongst accessions in the group. Also, average head girth (circumference in cm) and days to 50% booting were significant ($P<0.05$) with mean values of 9.0cm and 110.6 days as shown in Table 4.7. There was a wide variation in the head length and plant height ranging from 17.17cm (SARMIL 012) and 263.5cm (SARMIL 056) to 24.25cm and 368cm (SARMIL 108) with overall mean value of 20.92cm and 318.5cm respectively (Appendix IV-C). Average total tiller plant^{-1} also ranged from five for SARMIL 031 to as high as 12 in SARMIL 040, with a mean of 7.8 tillers plant^{-1}. The total plant plot^{-1} varied from 13 for SARMIL 030 to 21 for SARMIL 012 with a mean of 16 plant plot^{-1}. SARMIL 033 attained 50% booting at 123 days after planting which was significantly later compared with the other 21 accessions (46.7%) within the group (Appendix IV-C). However, the other 21 accessions did not exhibit any statistical difference amongst one another.

Even though percentage downy mildew (DM) incidence (both at 30 days after planting and at dough stage), average stover yield and productive tillers plant^{-1} did not reveal any statistical significance, there was a general increasing trend (average of 7.40% at 30 days to 24.20 % at dough stage) for downy mildew incidence with plants age (Table 4.7). Five accessions (SARMIL 038, 042, 061, 073, and 074) produced above 1.0kg stover yield plant^{-1}. The mean yield for the group was 0.737kg. Mean productive tillers plant^{-1} was also 3.39.

Table 4.7: ANOVA (Mean squares) for selected agronomic traits of the late-maturing group at Manga

Source of variation	df	DM at 30 days	DM at maturity	Average head girth	Average head length	Average plant Height	Stover yield	1000 seed weight	Average total tillers	Average prod've tillers	DFF	Plant stand/plot
Replication	3	2144.5	2019.4	2.695	7.308	95026	7.6228	36.196	3.6	0.1	227.21	226.21
Accession	44	133.90NS	371.60NS	2.251*	23.534**	2265**	0.1399NS	7.530**	5.876**	2.293NS	78.16*	27.44**
Error	132	120	362.8	1.479	8.958	1268	0.1637	3.11	1.895	1.509	47.3	15.86
Total	179	179	179	179	179	179	179	179	179	179	179	179

** Significant at 1%, NS: Not Significant; DM = Downy mildew, DFF=Days to 50% flowering, df= Degree of freedom, prod‘ve = productive

4.3.3 Summary of selected quantitative traits means for the maturity groups

There were quantitative variations among the accessions. In most of the cases the earlymaturing group showed clear variations. Percentage downy mildew (DM) incidence (except at dough stage for early-maturing group), average stover yield pant^{-1} and productive tillers plant^{-1} did not reveal any significance difference ($P<0.05$. From the results in Table 4.8, the mean plant height increased as mean stover yield plant^{-1} increased. This was observed with the medium-maturing group which had the highest stover yield plant^{-1} (1.064kg) as well as the highest mean plant height (341.3cm) followed by late-maturing group (318.5cm and 0.731kg) with the early-maturing group having the least Stover yield and plant height (0.297kg and 159.8cm, respectively).

Whereas the medium-maturing group was superior to the early and late-maturing groups in terms of mean head length (23.83cm, 18.31cm and 20.92cm respectively, Table 4.8), the early-maturing group performed better than the medium in respect of mean thousand seed weight (Table 4.8), producing the boldest seeds (1000 seed weight of 10.39g) while the medium- and late-maturing groups had mean weights less than 10g (9.45 and 7.64g, respectively).

Table 4.8: Mean values of growth and reproductive traits as influenced by time to maturity at Manga station.

Parameter taken	Grand Mean for the maturity groups		
	Early-maturing	Medium-maturing	Late-maturing
DM incid @ 30 days (%)	11.30	7.47	7.40
DM incid @ 70 days (%)	39.60	23.90	24.20
Average head girth (cm)	8.36	8.40	9.00
Average head length (cm)	18.31	23.83	20.92
Average plant height (cm)	159.80	341.30	318.50
Stover yield (kg) plant^{-1}	0.297	1.064	0.731
Thousand seed weight (g)	10.39	9.45	7.64
Average total tillers plant^{-1}	6.00	7.00	8.00
Average productive tillers plant^{-1}	4.00	5.00	3.00
Days to 50% booting	40.00	84.81	110.61
Plant stand plot^{-1}	16.07	16.29	15.98

DM = Downy mildew

4.4 Agronomic traits observation and UPGMA clustering analysis

The 123 accessions were handled as three distinct groups in line with Table 4.4 as early, medium, and late. This was done for easy and effective handling of the results as well as obtaining clearer dendrograms. The agronomic data (both qualitative and quantitative) gathered was transformed into present and absent and then used to construct three separate UPGMA, on a Jaccard‘s coefficient scale of 0-1, based on maturity grouping.

clustering a

4.4.1. UPGMA nalysis of 24 early-maturing accessions

A total of 15 quantitative and qualitative agronomic traits were used to construct the UPGMA and at a coefficient of 0.69, three distinct clusters were produced (Figure. 4.4). As stated earlier, the early-maturing group was constituted by accessions from Northern and Upper East Regions. Cluster A had only one accession (SARMIL 092) which happens to come from the Bongo district of Upper East Region and was influenced mainly by quantitative agronomic traits (Appendix IV-A) especially stover yield plant^{-1}. It was only similar to the rest of the group at 0.65 on the scale.

Cluster B was made up of 12 (50%) of the total 24 accessions whiles cluster C contained 11 (45.83 %) accessions. Clusters B and C each contained one set of duplicates at 0.95 on a scale of 0-1 (SARMIL 105 & 119 for B and SARMIL 111 & 115 for C) which came from different locations even though closed to each other (Appendix II) in terms of location.

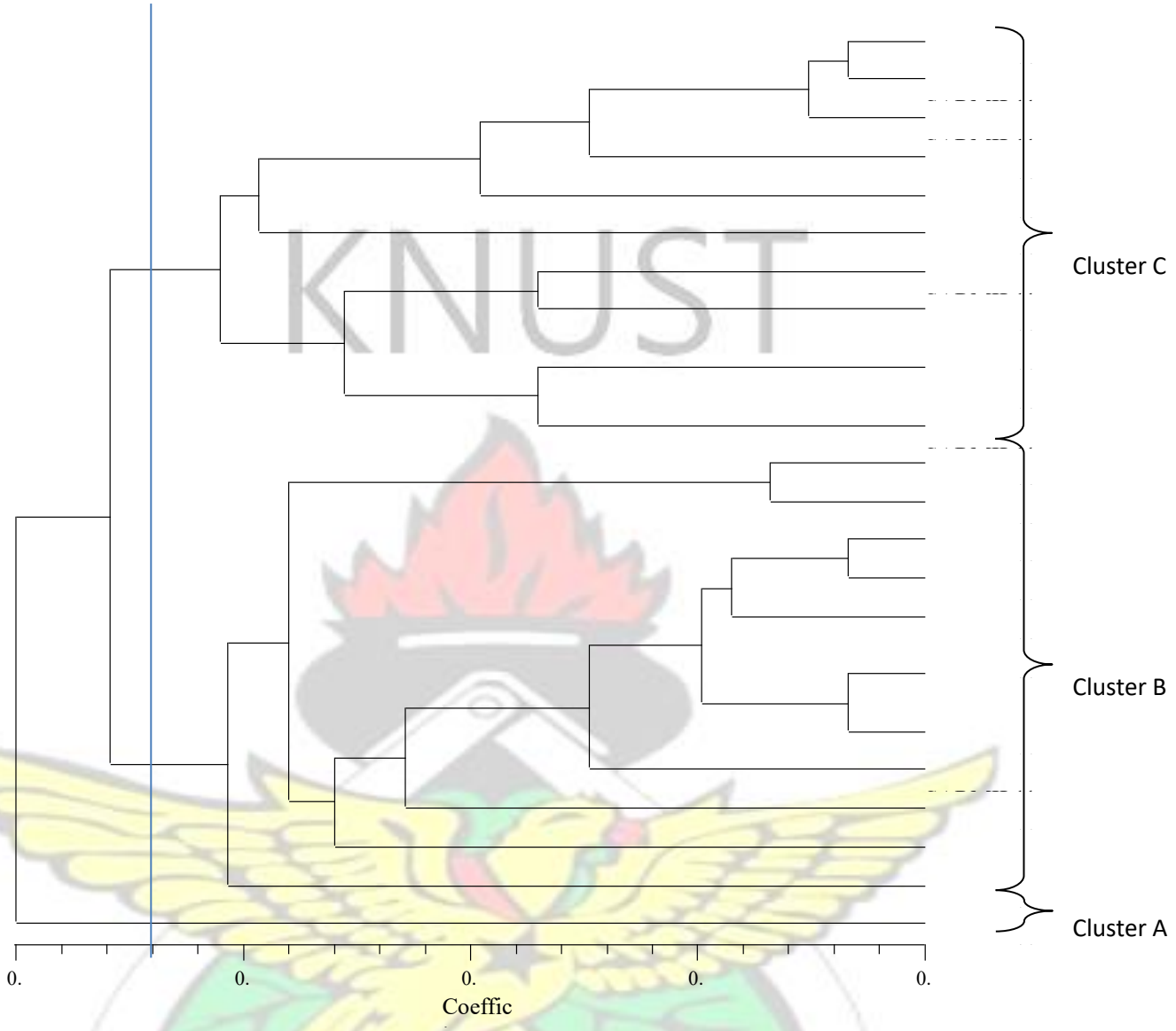

Figure 4.4: UPGMA phylogenetic analyses of agronomic traits of 24 Early-maturing Pearl millet accessions in northern Ghana (NTSYS-pc). The tree is constructed based on fifteen agronomic traits and clustering demonstrated at a Jaccard's coefficient of 0.692 (vertical line)

4.4.2. UPGMA nalysis of 54 medium-maturing accessions

Fifteen quantitative and qualitative agronomic traits were employed, using UPGMA method, for the divergence among the 53 accessions. At Jaccard's similarity co-efficient of 0.55 (Figure.4.5), five main clusters were observed.

clustering a

Cluster 1 consisted of SARMIL 011, SARMIL 016 and SARMIL 017 (5.6%), Cluster 2 was made up of SARMIL 003, SARMIL 004, SARMIL 009, SARMIL 018, SARMIL 051, SARMIL 067, SARMIL 078 and SARMIL 095 (14.8%), cluster 4 made up of SARMIL 045 and SARMIL 070 (3.7%) and 40 other accessions (74.1%) belonging to Cluster 5. SARMIL 044 (1.9%) stood alone as a unique one among the entire collection as cluster 3 and had its source from the Savelugu District of Northern Region.

The groupings revealed that all cluster 1 accessions (Figure 4.5) came from Upper West Region and in communities such as Hapan-Hamile, Wuli and Chabatan-Babile in LambuseiKarni, Jerapa and Lawra (Appendix II) Districts respectively along the border with Burkina Faso. Clusters 2 and 5 accessions cut across all three Regions, with Upper West contributing about half (two each from Sisala West and Lawra Districts) to accessions of cluster 2. The two members of cluster 4 came from Northern Region but from different Districts. Accessions SARMIL 065 and SARMIL 059 belonging to cluster 5 in Figure 4.5 were observed to be duplicates (with coefficient of 1.00) even though they were from different districts (Chereponi and Yendi, respectively) in the Northern Region.

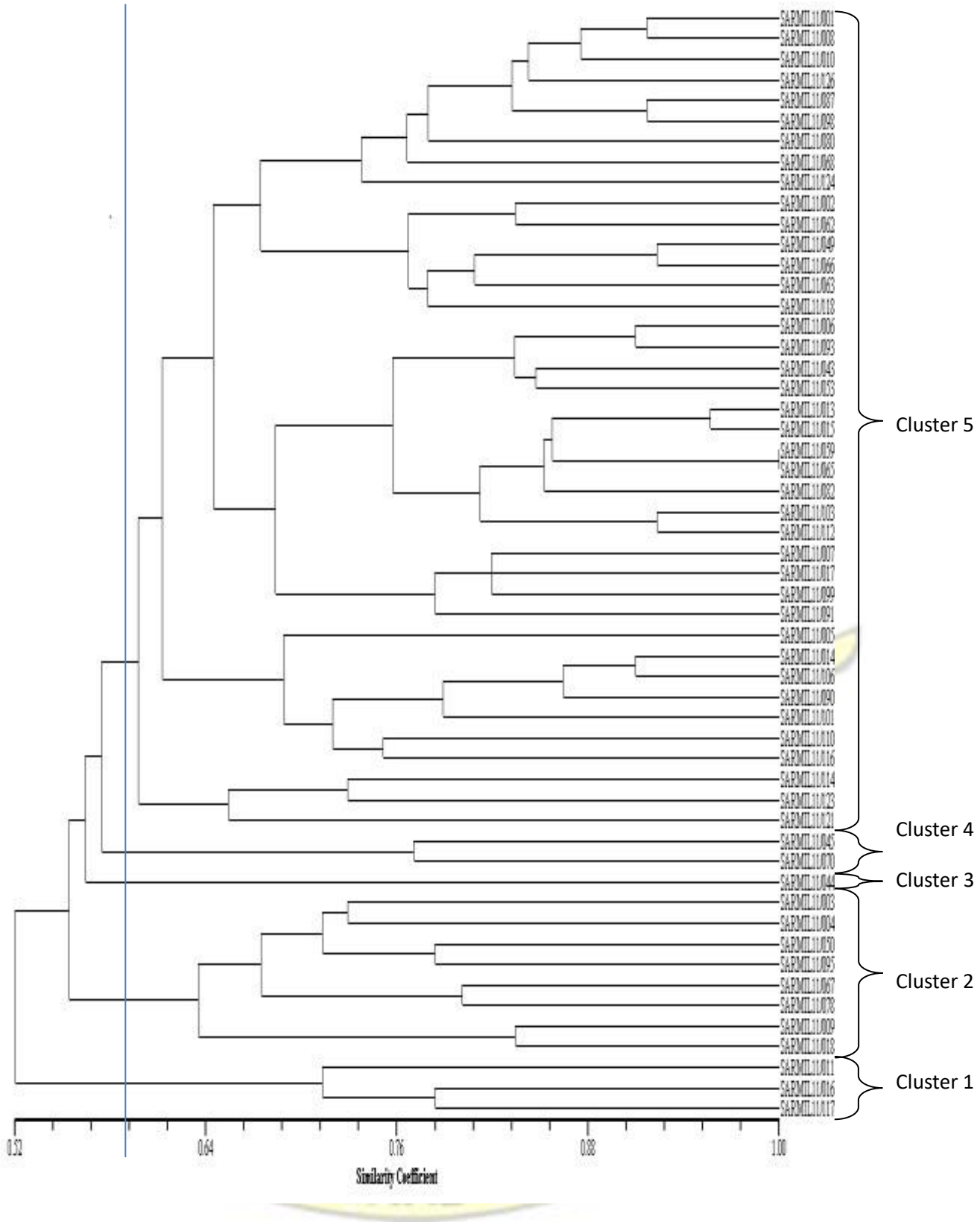

Figure 4.5: UPGMA phylogenetic analysis of agronomic traits of 53 medium-maturing Pearl millet accessions in northern Ghana (NTSYS-pc). The tree is constructed based on fifteen agronomic traits and clustering demonstrated at a Jaccard's coefficient of 0.552 (vertical line)

clustering a

4.4.3. UPGMA nalysis of 45 late-maturing accessions

For the late-maturing accessions five (5) clusters (I: 2.2%, II: 17.8%, III: 8.9%, IV: 60.0% and V: 11.1% of total accessions) were produced from a total of 45 accessions using a coefficient of 0.69 (Figure 4.6). Cluster I had SARMIL 026 as the only accession and its origin was traced to the Wa central district of Upper West Region (Appendix II) and was only related to the other clusters at co-efficient of 0.63 on the scale. Even though it possessed similar qualitative traits as SARMIL 048 in cluster IV, they differed in some quantitative traits such as downy mildew incidence and plant height. Cluster IV was the largest with 27 of the accessions. However, there were two sets of duplicates (at 0.95) in this cluster. SARMIL 019 and SARMIL 028 as one set and SARMIL 021 and SARMIL 034 as another set appeared to have been influenced more by head and grain qualities and not location. Cluster II consisting of SARMIL 025, SARMIL 031, SARMIL 032, SARMIL 038, SARMIL 040, SARMIL 052, SARMIL 054 and SARMIL 057 was the second largest group. Clusters III was made up four accessions namely SARMIL 046, SARMIL 050, SARMIL 056 and

SARMIL 058 while cluster V had five accessions consisting of SARMIL 012, SARMIL 041, SARMIL 042, SARMIL 060 and SARMIL 061.

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Cluster IV

Cluster III

Cluster II

Cluster I

clustering a

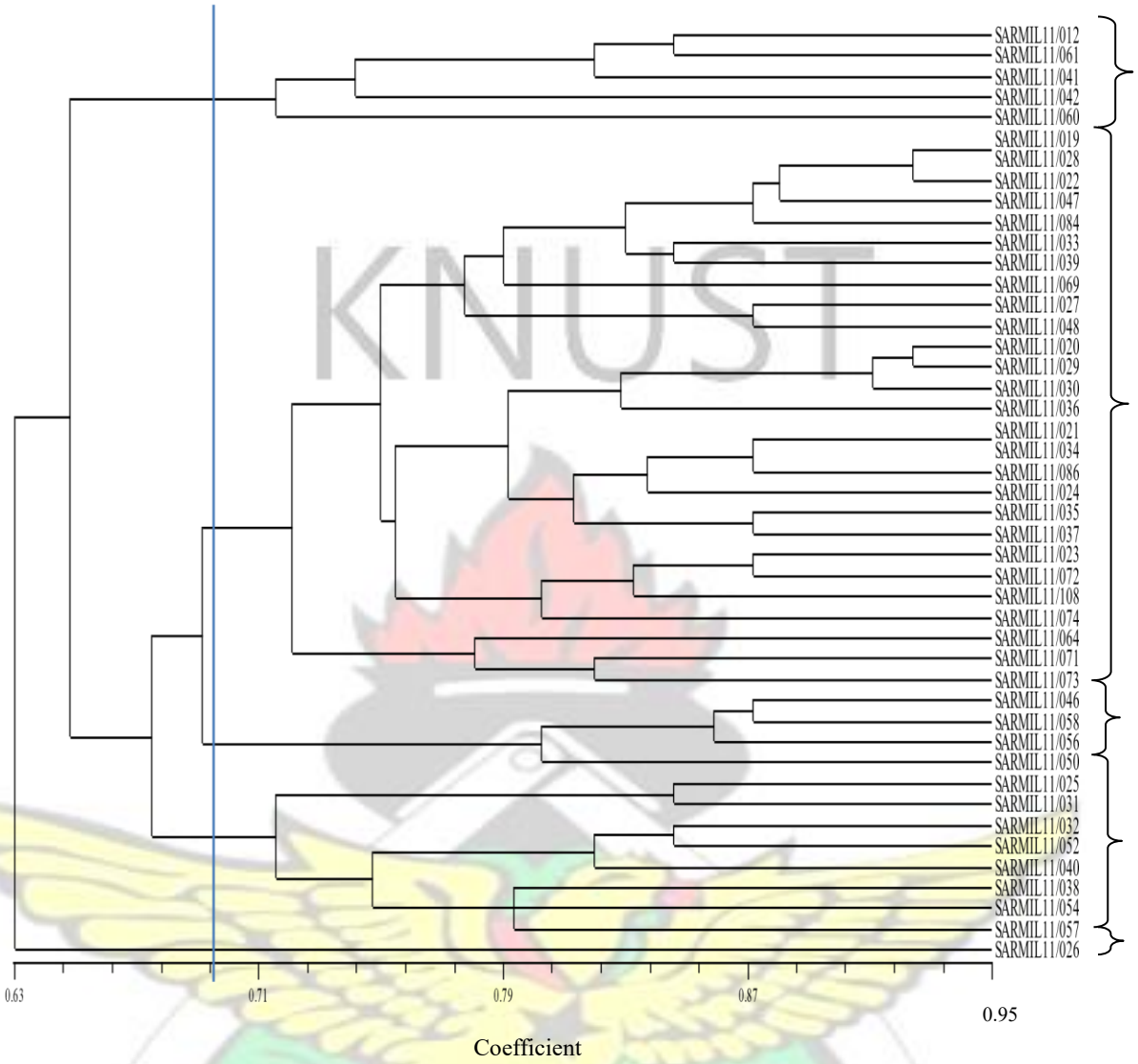

Figure 4.6: UPGMA phylogenetic analysis of agronomic traits of 45 Late-maturing Pearl millet accessions in northern Ghana (NTSYS-pc). The tree is constructed based on fifteen agronomic traits and clustering demonstrated at a Jaccard's coefficient of 0.694 (vertical line)

4.5 Genetic diversity and relationships among 119 accessions using microsatellites

A total of 119 out of the 123 accessions were genotyped using 36 Simple Sequence Repeats (SSR) polymorphic markers designed for Pearl millet. The four (SARMIL 025, 034, 061 & 093) were not genotyped because of poor quality of extracted DNA.

The results showed a wide diversity among the collections within each maturity group as well as the entire accessions treated as a whole.

4.5.1 Combined gene diversity analysis

Generally the analysis of the 119 accessions (Table 4.9) revealed that the average number of alleles per microsatellite was 8.8. The range was from 3.0 alleles in Xpsmp2246 and Xpsmp2201 to 20 alleles in Xpsmp2068 and Xpsmp2270. 41.67% (15 microsatellites) had allele numbers ranging from 10 to 20. The results indicated that the PIC ranged from 0.142 to 0.927 for M13-Xpsmp2077 and Xpsmp2068, respectively with mean value of 0.613. M13Xpsmp2077 had the lowest expected heterozygosity and observed heterozygosity (Ho) values of 0.145 and 0.108 respectively. Xpsmp2068 and Xpsmp2266 recorded the highest values of 0.932 and 0.579 respectively for expected and observed heterozygosity. A look at the various maturity groupings revealed a number of interesting observations and contributions of some microsatellites to the gene diversity (Appendixes V-E, M, L) hence it became necessary to present them separately.

Table 4.9: Genetic diversity analysis using 36 polymorphic microsatellite primers in 119 Pearl millet accessions

Marker	Major Allele Frquency	NA	He	Ho	PIC	Min bp	Max bp
XPsmp2246	0.577	3	0.555	0.333	0.477	260	264
M13_Xpsmp2077	0.923	6	0.145	0.108	0.142	154	198
Xpsmp2276	0.455	8	0.712	0.402	0.675	266	286
Xctm12	0.409	10	0.761	0.261	0.733	319	335
Xicmp3027	0.288	5	0.755	0.542	0.711	198	208
Xpsmp2233	0.310	8	0.774	0.195	0.739	254	268
Xpsmp2085	0.509	5	0.630	0.410	0.570	166	174
Xpsmp2248	0.680	5	0.488	0.386	0.440	158	172
Xicmp3050	0.652	6	0.494	0.393	0.425	213	227
Xicmp3032	0.496	7	0.654	0.398	0.600	184	202
Xpsmp2232	0.366	7	0.738	0.361	0.694	223	241
Xpsmp2249	0.835	5	0.292	0.206	0.278	128	154
Xpsmp2261	0.280	15	0.832	0.505	0.812	175	199
M13_Xpsmp2206	0.528	7	0.663	0.449	0.629	217	231
Xpsmp2210	0.233	17	0.877	0.466	0.866	298	344
Xpsmp2270	0.250	20	0.889	0.388	0.881	138	188
Xpsmp2275	0.697	6	0.445	0.294	0.378	270	282
Xpsmp2277	0.453	10	0.721	0.402	0.688	228	258
Xpsmp2224	0.557	6	0.597	0.470	0.536	150	162
Xicmp3002	0.733	4	0.418	0.271	0.369	198	208
Xpsmp2219	0.466	7	0.661	0.458	0.604	229	291
M13_Xpsmp2086	0.449	12	0.730	0.188	0.700	108	148
M13_Xpsmp2030	0.688	10	0.508	0.286	0.490	127	153
Xpsmp2045	0.332	12	0.767	0.445	0.732	193	217
Xpsmp2080	0.318	12	0.823	0.365	0.804	144	196
M13_Xpsmp2203	0.245	10	0.814	0.545	0.788	353	377
Xpsmp2222	0.513	4	0.633	0.440	0.573	153	159
Xpsmp2068	0.119	20	0.932	0.496	0.927	98	138
Xpsmp2266	0.254	10	0.810	0.579	0.783	172	192
Xpsmp2201	0.856	3	0.255	0.127	0.237	346	366
Xpsmp2208	0.496	11	0.700	0.431	0.672	245	317
Xpsmp2227	0.809	4	0.326	0.280	0.302	195	211
M13_Xctm10	0.189	15	0.900	0.351	0.892	188	216
M13_Xpsmp2087	0.398	6	0.662	0.519	0.595	137	151
M13_Xpsmp2090	0.382	13	0.798	0.325	0.779	193	213
M13_Xpsmp2273	0.604	7	0.576	0.167	0.532	185	213
Mean	0.482	8.8	0.648	0.368	0.613		

NA: allele number, He: expected heterozygosity, Ho: observed heterozygosity, PIC: polymorphic information content, Min bp: minimum base pair, Max bp: Maximum base pair

4.5.2 Gene diversity analysis of the early-maturing group

In the case of the early-maturing group, the mean PIC value was 0.604 with a range of 0.099 to 0.901 for Xpsmp2249 and M13-Xctm10, respectively (Appendix V-E). Sixteen (44.44%) of the microsatellites had PIC values below the mean. Also the number of alleles per microsatellite ranged from three (7 microsatellites) to fourteen in Xpsmp2068 with a mean of 6.1. Xpsmp2261, Xpsmp2210, Xpsmp2068, Xpsmp2208 and M13-Xctm10 had 10, 11, 14, 10 and 12 alleles each in that order. The gene diversity value ranged between 0.101 for Xpsmp2249 and 0.908 for M13-Xctm10. The mean value for gene diversity was 0.644. For the expected heterozygosity, the mean value was 0.337 with the range being 0.105 (Xpsmp2249) to 0.542 (Xpsmp2227)

4.5.3 Gene diversity analysis of the medium-maturing group

The trend was similar in the medium-maturing group just as the early-maturing groups. The PIC mean value was 0.580 from values that range from 0.037 for Xpsmp2201 to 0.922 for Xpsmp2068. Whereas mean value for gene diversity was 0.615, the value for heterozygosity was 0.340. The range for gene diversity was from 0.038 (Xpsmp2201) to 0.927 (Xpsmp2068) while that for heterozygosity was from 0.038 (Xpsmp2201) to 0.673 (Xicmp3027). With a mean number 7.0 alleles per microsatellites, the results from the medium-maturing group revealed a range from 2 (Xpsmp2201) to as many as 19 (Xpsmp2068) alleles per microsatellite. Except for heterozygosity, Xpsmp2201 and Xpsmp2068 respectively recorded the lowest and highest values for PIC, gene diversity and allele number. Even though Xpsmp2201 still recorded the lowest value for heterozygosity, the highest value recorded was with Xicmp3027.

4.5.4 Gene diversity analysis of the late-maturing group

The mean number of alleles per microsatellite locus for the late-maturing was 6.7 with a range of 2 alleles for Xpsmp2201 to 16 in Xpsmp2068. Seven microsatellites loci had allele values of ten and above, and 17 having values above the mean value of 6.7. The PIC value of the 36 microsatellite loci ranged from 0.067 to 0.908 with an average value of 0.578. The observed heterozygosity (Ho) had a mean value of 0.408 and ranged from 0.071 to 0.732 (for Xpsmp2201 and Xpsmp2266 respectively). Similarly, the value for expected heterozygosity (He) ranged from 0.069 in Xpsmp2201 to 0.915 in Xpsmp2068 with a mean value of 0.616.

4.6 Accessions selected as core collection

Based on the agronomic traits used and the results generated by the cluster analysis, it was possible to identify accessions that could best represent the entire collection. These were made up of seven (29.2%), 13 (24.1%) and 10 (22.2%) accessions from the early, medium and late maturity groupings, respectively (Table 4.10). Of the seven from the early maturity group, one was from Northern Region while the other six were from Upper East Region.

With medium maturity group, Upper West and Northern Regions contributed four each while five came from Upper East region. In the case of the late maturity group, Northern Region contributed the largest number of seven followed by Upper West with two and Upper East contributing one accession. In all, 30 core selections were made which represented 24.39% of the entire collection. On Regional basis, 12, 6 and 12 accessions were selected from Upper East, Upper West and the Northern Region, respectively as core collection.

Table 4.10: Selected core Pearl millet accessions collected from Upper East, Upper West and Northern regions of Ghana based on cluster analysis of maturity groupings

Region	Maturity group			Total
	Early	Medium	Late	
Upper East	SARMIL 085, SARMIL 092, SARMIL 097, SARMIL 102, SARMIL 104, SARMIL 113	SARMIL 091, SARMIL 095, SARMIL 110, SARMIL 121, SARMIL 124	SARMIL 084	12 (27.27%)
Upper West	0	SARMIL 002, SARMIL 005, SARMIL 009, SARMIL 016	SARMIL 024, SARMIL 026	6 (23.08%)
Northern	SARMIL 077	SARMIL 044, SARMIL 053, SARMIL 070, SARMIL 082	SARMIL 036, SARMIL 050, SARMIL 054, SARMIL 060, SARMIL 064, SARMIL 069, SARMIL 074	12 (22.64%)
Total	7 (29.2 %)	13 (24.1 %)	10 (22.2 %)	30 (24.4 %)

CHAPTER FIVE

DISCUSSION

The agro-morphological and genetic diversity results indicate a wide range of variation for most of the traits and this will serve as a very good source of genetic variation and valuable genes for Pearl millet breeding work in Ghana and beyond.

5.1 Crop ecology

The soil properties and fertility status of the field typified the situation of northern Ghana – loamy-sand and acidic – which is ideal for Pearl millet cultivation (Spencer and Sivakumar, 1987). However, the percentage Organic Carbon (OC) was observed to be low (0.62%) in the evaluation field compared with the global outlook of 1.1 – 2.5 (SRID, 2010)

Constant decline in the annual precipitation amounts has been blamed on climate change over the years (Kasei 2001) affecting the ecology of the crop. This is an indication that the seasons are getting shorter by the day. According to Appa Rao *et al.* (1985), the mean annual rainfall for northern Ghana was 1,000 to 1,200 with bimodal rainy season (with peaks in May-June and October) in the 1980. The situation has changed with the area experiencing only one rainy season with a peak in August-September. The climate change effect has rather reinforced the need to concentrate more efforts at developing and conserving the earlymaturing accessions for the ecology of northern Ghana.

5.2 Ethno-botanical variations within the accessions

Pearl millet grain is used in Ghana for the preparation of traditional dishes such as _koko‘ (light porridge) _masa‘ (fried cake) and _tuo-zafi‘ (thick porridge), while the stalks are used as fuel and fencing in most households, confirming the report of Appa Rao *et al*. (1985). Also none of the accessions/landraces collected was an improved or introduced material. The main

source of seed supply has been to maintain their previous harvest or contact a neighbour for supply in case of total loss seed. This is because of the subsistence nature of agriculture practiced by farmers throughout the interior savannah (Appa Rao *et al*. 1985). This practice may have contributed to the close relationship that exists between and among some accessions from some neighbouring districts.

The number of collections made reflected the total land mass of the Region and the relative importance of the crop to the people of each Region. Upper East had the highest number of accessions (21 out of 24) in the early-maturing group because the area is noted to practice mixed cereal cropping involving sorghum, millet, and maize of which millet is always the first crop planted to harvest early in the season. The Region is also noted for its high production and consumption of Pearl millet in Ghana and hence the relatively high number of accessions/landraces that were gathered compared with Northern Region. Upper West did not record any early-maturing group because of incidence of bird attack over the years which have led to farmers abandoning the crop (personal interview). Almost every farm household in the Upper East Region grows early-maturing millet with the on-set of the early rains which is later intercropped with late-maturing millet, sorghum or a mixture of sorghum and latematuring millet. A system of farming where the immediate surroundings of the homesteads are often cropped with a mixture of different crops with different maturity period is a common feature in the Upper East Region. This ensures that early-maturing millet is well accommodated in the practice. It is suspected that the three early-maturing millet accessions collected from Northern Region were carried there by settlers from Upper East Region since these communities share boundaries with Upper East Region.

Upper West and Northern Regions were observed as home of the late-maturing group of Pearl millet as they contributed 93.3% of total accessions collected. This trend could be attributed to the ecology since these Regions receive more precipitation than Upper East

Region over the years. Also these regions tend to have more ―bush farms‖ where earlymaturing millet is not preferred.

All the farmers from whom samples were collected indicated that they always maintain their own seed stock year-after-year. This is the practice handed down from generations. Only nine farmers (7.1%) mentioned diseases such as downy mildew, stem borers, leaf folding and leaf drying as well as drying of whorls as having effect on Pearl millet production while the over 92% donors did not recognise any diseases associated with Pearl millet.

The main desired traits that farmers look out for in Pearl millet are Striga resistance, drought tolerance, early maturity, seed colour as well as ability to grow under very poor and marginal soils. The late maturing types were preferred for bush farms since birds do not normally attack them due to abundance of weed seed at the time of maturity.

Sawla-Tuna, West Mamprusi and Bunkpurugu-Yunyoo districts each contributed two accessions to early maturity group (according to donors). West Mamprusi and BunkpuruguYunyoo Districts actually share boundaries with southern part of Upper East Region. However, the morpho-agronomic data indicated that the two early maturing collections from the Sawla-Tuna District were rather late maturing.

5.3 Qualitative trait variations within the accessions

Only two head (spike) types namely lose and semi-compact heads were revealed by the collections. However majority (101 accessions) were the semi-compact type. Within the maturity groupings, the medium had the highest number of 46 accessions being semicompact while the early had the least of 17 accessions showing this same trait. The variations observed here do not agree with what has been reported by Khairwal *et al*. (2007) using core collections

under Indian conditions which showed extensive variations. This means it is possible to encounter wide variation in Pearl millet landraces in Ghana if the collections were done on the field during the crop growth. In terms of head shape types, 110 (89.43%) of the accessions had cylindrical head shape while 13 (10.57%) were candle shaped. Even though the results were consistent with those obtained by Appa Rao *et al*. (1985), it did not include conical head shape as reported by the latter. This is confirmed by the fact that some of the accessions that were observed to have cylindrical head shapes in Ghana became either spindle or conical and vice-ci-versa in India (Appa Rao *et al*. 1985). It is sometimes difficult to draw the line between cylindrical and conical head shapes and this might have resulted in the current accessions showing more cylindrical while those studied by Appa Rao and others showing majority being conical.

Following the codes provided by the Royal Horticultural Society, the Ghanaian accessions exhibited five main seed colours of ivory, yellow, grey, deep-grey and brown-grey during the evaluation. The colour grey and deep-grey constituted the largest group (80.50 %) and agrees with Appa Rao and others that the Ghanaian Pearl millet is dominated by grey grain colour.

5.4 Quantitative morpho-agronomic variations within the accessions

There were significant variations in response to downy mildew incidence among the earlymaturing group at dough stage. This phenomenon is useful for trait identification when targeting downy mildew in any breeding programme. However there was a general increasing trend in downy mildew incidence for all maturity groups. According to Arun and Manga (2011) environmental factors such as temperature, humidity, rainfall cloudiness and intensity of radiation all influence downy mildew development and spread as well as the disease cycle of the *Sclerospora graminicola* (Sacc.) Schroet pathogen. This probably explains the progressive

increase in the incidence observed. The medium-maturing and late-maturing groups had lower incidences than the early-maturing. This is due likely to the fact that the former mature at a time that the environmental conditions are not favourable for disease development.

The incidence levels recorded indicated that some of the materials were resistant (<10 %) while others were susceptible (>10 %) to the downy mildew disease. However, accessions such as SARMIL 083 and SARMIL 125 of early-maturing group, SARMIL 010, SARMIL 099 SARMIL 112 and SARMIL 126 of medium-maturing group and SARMIL 021, SARMIL 028, SARMIL 033 and SARMIL 073 of the late-maturing group (Appendix IV-A, B & C) all recorded zero disease incidence at 30 days after planting. At dough stage all except SARMIL 010 (medium-maturing) had succumbed to the disease and recorded values ranging from 10.0 % in SARMIL 115 (medium-maturing) to 45.0 % in SARMIL 083 (earlymaturing). The mean downy mildew values recorded for early-maturing, medium-maturing and late-maturing groups (Appendix IV-D), show that the Ghanaian Pearl millet generally has problems with downy mildew and therefore require good timing on when to plant during the year. Arun and Manga (2011) reported that yield loss attributed to downy mildew is incomplete due to variability in incidence from field to field, from farmer to farmer and from season to season. But Wilson *et al*. (2008), in studies conducted in some West African countries, revealed that downy mildew incidence is negatively correlated with grain yield. However, Singh *et al*. (1999) reported that global yield loss due to downy mildew may not exceed 20% even though there were localised situations, especially in India, where yield loss could go as high as 40%. These values are however lower than what has been reported by Nutsugah and Atokple (2002). Their report indicates that downy mildew is the most important disease limiting Pearl millet production in Ghana, contributing up to 60% grain yield losses annually.

On the average, the early-maturing group had plants with the shortest height (160cm) and head lengths (18.31cm) while the medium-maturing group had the tallest (394.5cm) plants and longest heads (23.83cm). The results are fairly consistent with Appa Rao *et al*. (1985) who reported a range of 39 – 140 days, 120 – 315cm and 6 – 53cm for days to fifty per cent flowering, plant height and head length respectively, for Ghanaian landraces. Generally these traits tend to positively correlate with grain yield in most locations in West Africa where Pearl millet is grown (Wilson *et al*., 2008). The variations in head length are attributed to the allogamy in Pearl millet. Trait affecting head size of Pearl millet cultivars is reported to exert a considerable amount of influence on its productivity (Rachie and Majmudar, 1980, Khaiwal and Singh, 1999) and is appreciated in breeding of improved cultivars. Appa Rao *et al*. (1985) reported that there are only two maturities; early- and late-maturing groups in the Ghanaian Pearl millet and that the differences in flowering between them are determined by 2 genes, L1 and L2 without dominance. However within the early-maturing group, several genes govern flowering with additive effect is reported (Bilquez and Clement, 1969). This probably explains the variations in the accessions evaluated. The maturity groupings in the current studies are different from what has been reported. For instance Appa Rao *et al*. (1985) considered 70 days as the upper limit for the early-maturing group and 71 days as the lower limits for the late-maturing group. In the current studies however, that was not the case. However both the medium and late types in the current studies were harvested between early October and mid-December. It was therefore prudent to separate these into two different groups. The late-maturing ones can be recommended for bush fields while the mediummaturing are maintained for the compound farms.

In terms of productive tillers and thousand seed weight, the evaluated accessions had mean value of four (4) with a range of 1 – 8 tillers per plant while the mean value for seed weight was 9.16 g (ranged between 4.53 g and 12.21). This shows the potential of the material for

yield and biomass improvement since tillering is positively correlated with grain and fodder yields as suggested by Harer and Karad (1998) and Khairwal *et al*. (2007). However the result deviated from others (Appa Rao *et al*. 1985; Afribeh, 2005) who asserted that the Ghanaian Pearl millet populations have a range of 1 – 3 tillers per plant. Consumer preference of a cultivar is often influenced by grain size (bold grains), and by extension grain yield and quality hence an important trait in Pearl millet (Haidara *et al*. 1987). According to Rai *et al*. (2009), grain sizes can be categorised into very small (<5g per 1000), small (5.0 – 7.50g per 1000), medium (7.6 – 10.0g per 1000), bold (10.1 – 12.50g per 1000) and very bold (>12.50g) grains. In the current studies only SARMIL 041 had very small grain, 23 accessions had small, 72 had Medium, and 27 had bold grain. These variations corroborate reports by Appa Rao *et al.* (1985).

Generally the results did not show any pattern to suggest that certain agronomic traits are the preserve of a particular location or region of Ghana. Thus it is possible to use any accession at any location within the area. The fact that farmers in Northern and Upper West Regions are not growing the early-maturing millet types is purely based on farmers' interest or choice.

Khairwal *et al*. (2007), evaluating over 3000 lines, landraces and accessions in India in 2006 revealed an extensive variation for most traits. It was therefore not surprising to have the accessions exhibiting such a variation in most of the traits evaluated. This variation in traits will obviously serve as a gene diversity pool for future improvement in the Pearl millet crop.

5.5 Relationship among accessions from the UPGMA clustering

The tree cluster for the early-maturing group indicated that clusters B and C were both influenced by three seed shapes such as obovate, hexagonal and globular. Majority of the seed were globular in shape followed by hexagonal with the least being obovate. Again it was observed that whereas cluster C was influenced by grey, deep-grey and deep-brown seed colours, cluster B was deep-grey seed colour. Both clusters had up to seven districts each contributing accession to them with cluster B having two out of the three accessions from Northern Region. This confirms reports by Appa Rao *et al*. (1985).

With regards to the medium-maturing group, qualitative traits such as head shape and seed colour influenced cluster 1. These were grey and deep-grey seed colours as well as cylindrical and candle head shapes. In cluster 2, obovate and globular (75.0% and 25.0% respectively) seed shapes together with cylindrical and candle (75.0% and 25.0% respectively) head shapes influenced the cluster. Apart from seed and head shapes, seed colours such as yellow seed (50%), ivory (25%), grey and deep-grey (12.5% each) also influenced the cluster.

All members of cluster II (except SARMIL 025 collected from Upper West) in the latematuring group were collected from Northern Region and were influenced heavily by semicompact and cylindrical head type (87.5%) as well as grey and globular seed colour and shape types (75.0%). Members of cluster III were from Northern Region and exhibited complete homogeneity, showing cylindrical semi-compact heads, having globular grains and grey colour. Members of cluster IV cut across the three Regions and were made up of eighteen (66.7%), six (22.2%) and three (11.1%) from Northern, Upper West and Upper East Regions, respectively. The cluster tended to be dominated by cylindrical semi-compact head type and globular seed shape. All the accessions from Upper West in this cluster were from neighbouring Districts (Nadowle, Wa East and Wa Central) in Upper West region.

The nature of clustering as revealed by the various maturity groups is significant in determining core collection. The uniqueness of the clusters confirms variations among the Ghanaian landraces reported by Appa Rao *et al*. (1985) and for Pearl millet in general (Khairwal *et al*. (2007).

5.6 Molecular marker diversity within the accessions

Broadening the genetic base of any crop is very important since inbreeding often lead to a reduction in genetic diversity, more so with open pollinated crop like Pearl millet. Key to Pearl millet germplasm preservation in Ghana is an understanding of the genetic relationship and diversity among available collections. Genetic diversity estimates relies very much on the number of alleles within the population and this helps in comparing two or more accessions or landraces. From the 119 accessions genotyped, a total of 316 alleles were recorded with 36 microsatellites and an average of 8.8 alleles per locus. Considering the accessions by maturity grouping, the results were 221, 252 and 240 alleles for early, medium and late maturity groups respectively. The mean alleles per locus were, early; 6.1, medium; 7.0 and late; 6.7. These results indicate a very high level of polymorphism at the loci and thus a very high level of genetic diversity among the Pearl millet accessions. Heng-Sheng *et al*. (2012), working on foxtail millet and using 40 microsatellites, had 2.4 alleles per locus which was considered to be high. Therefore the observed 8.8 alleles per locus for Pearl millet is thus significantly higher than 2.5 and 6.16 alleles per locus reported by Jia *et al.* (2007; 2009) using SSR markers on foxtail millet, 4.91 alleles per locus in broomcorn reported by Cho *et al*. (2000), and 3.83 alleles per locus for rice in work done by Hu *et al*. (2009). The presence of significant genetic variation within the accessions is an indication that useful traits of many kinds are present in the collection and hence has the potentials for trait improvement through breeding. According to

Deb (2009), agricultural productivity and food security can be maintained through sustained crop diversity and by default genetic diversity. This will hold true for Pearl millet considering the erratic nature of rains in the last decade resulting from climate change effects as well as land use change.

In genetic analysis, the PIC value is used to measure the discriminatory power of a marker and there is evidence to show that there is a positive correlation between PIC and number of alleles per locus (Jia *et al*., 2009). A PIC value greater than 0.5 (PIC > 0.5) is considered high, and indicates that such marker can be effectively used in genetic diversity studies, especially in foxtail (Heng-Sheng *et al*., 2012). In the current work therefore, and taking the entire accessions as a whole, 26 (72.22%) microsatellites loci had PIC values above 0.5.

Similarly, the early, medium and late maturity groups respectively had 27 (75%), 24 (66.67%) and 26 (72.22%) microsatellites with PIC values above 0.5. These PIC values were considered as having high number of polymorphisms. The 119 accessions with the 36 microsatellites showed that eight (22.22%) and two (5.56%) microsatellites had medium ($0.25 \leq PIC < 0.5$) and low ($PIC < 0.25$) number of polymorphism respectively. Generally the mean PIC value (0.613) observed in this study compare favourably with those reported by Kapila *et al*. (2007), who reported an average PIC value of 0.58 for Pearl millet. In fact, the average PIC value for the medium maturing group in this study was the same as reported by

Kapila *et al*. (2007) while that of the early maturing group was 0.604.

The results revealed that the expected heterozygosity (He) ranged from 0.145 to 0.932 and the Observed Heterozygosity (Ho) ranged from 0.108 to 0.579 with average values of 0.648 and 0.368 respectively. The results for the three maturity groupings indicated that the average He for early, medium and late were 0.644, 0.615 and 0.616 respectively. Again 0.337, 0.340 and

0.408 were the average Ho for early, medium and late maturity groups respectively. The He values in this study are higher than average value of 0.354 reported by

Heng-Sheng *et al*. (2012) working on 324 foxtail millet and Cho *et al*. (2010), whose work on Proso millet recorded average He value of 0.37, but less than the average value of 0.67 reported by De Campos *et al*. (2008) whose work was on 126 wild rice. Also the mean Ho values (early; 0.337, medium; 0.340, late; 0.408 and overall; 0.368) for Pearl millet were observed to be higher than 0.045 for Indian foxtail millet (Gupta *et al*., 2012). The higher values obtained for He and Hobs could be attributed to the fact that Pearl millet is an open pollinated crop and that most of the farmers resorted to natural selection methods in preserving seed for regeneration year after year. These results have also demonstrated the potential genetic variability inherent in the collected Pearl millet accessions.

5.7 Core collection

Brown (1989) defined core collection as a _limited set of accessions derived from an existing collection, chose to represent the general spectrum in the collection‘. This should comprise a greater proportion of the genetic diversity as possible. Core collection can be used for precise evaluation of trait of agronomic importance and biotic and abiotic stresses as well as mapping with molecular markers for identification of trait-specific germplasm and discovery of new genes. The current work came up with a total of 30 core collection covering the entire area from where the collection was done. Also it covered the various maturity groupings, total number collected per region as well as the various clusters that resulted from the analysis.

The early maturity group for instance, had seven accessions in all as core and these comprised of one from Northern Region and six from Upper East Region since the collections did not produce any early maturing accessions from Upper West Region. Of the six accessions from

Upper East Region, care was taken that they were coming from the three clusters as well as representing Eastern (SARMIL 113 from Garu area), Western (SARMIL 097, SARMIL 104 and SARMIL 102 from Builsa and Navrongo areas) and Central (SARMIL 085 and SARMIL 092 from Tongo and Bongo areas) parts of the Region. The 13 and 10 core selections representing medium and late maturing groups respectively were selected using similar criteria.

Similarly all the agronomic traits studies were considered in coming out with the core selection. SARMIL 077, SARMIL 104 and SRMIL 113 for instance, were chosen for their earliness, head length and plant height qualities among the early group while SARMIL 092 had good stover quality. SARMIL 097 had good qualities in terms of head length (24.67 cm) and boldness of grain (10.67 g/1000 seed). SARMIL 002, SARMIL 005, SARMIL 009, SARMIL 016, all from Upper West Region and belonging to the medium maturing group, encompasses traits like high and low downy mildew, long heads, good stover yield, thick and thin head types among others.

According to Ranjana (2009) molecular profiles of group of accessions can be used to identify duplicates in a collection and thus reduce its size and maintenance cost. Having a small core of 30 accessions in the current work would therefore make it easy to effectively handle and programme Pearl millet breeding work in CSIR-SARI, Ghana.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1. Conclusions

The following conclusions were drawn from the studies conducted;

Annual reduction in the total number of rainy months over the years is having a big impact on agricultural in the three Regions of Northern Ghana. All farmers in the studied area are using their traditional early maturing Pearl millet landraces as planting material year after year. No new variety have been introduced to the area in the last 40 years. Pearl millet remains paramount in the food security system of drought-prone and infertile areas of Northern Ghana where it is used as a stop-gap to the hunger periods of June to September each year.

Again there was no clear-cut influence of Region on medium and late maturity grouping but Upper East dominated with early maturing type of Pearl millet. Generally the results did not show any pattern to suggest that certain agronomic traits are the preserve of a particular location or Region of Ghana. Thus it is possible to use any accession at any location within the area as breeding material.

The molecular results revealed significant genetic variations (both expected and observed) among the accessions collected. These variations will obviously serve as a gene diversity pool for any improvement on the Pearl millet crop. The higher values obtained for expected heterozygosity and observed heterozygosity, using microsatellites, could be attributed to the fact that Pearl millet is an open pollinated crop and that most of the farmers resorted to natural selection methods in preserving seed for regeneration year after year. These results also serve to demonstrate the potential genetic variability inherent in the collected Pearl millet accessions.

The local Pearl millet is rich in many important morpho-agronomic traits including resistance to downy mildew, varied plant height and short maturity which can be explored for breeding purposes. The Ghanaian Pearl millet generally has high levels of downy mildew incidence and therefore requires that care be taken during breeding programmes. Hence the core collection of 30 accessions in the current work would make it easy to effectively handle and programme

Pearl millet breeding work in CSIR-SARI and for that matter Ghana since this core would reflect almost the entire gene pool of Pearl millet grown in Northern Ghana.

6.2 Recommendations:

Efforts need to be concentrated more at developing and conserving the early-maturing accessions of Pearl millet for the ecology of Northern Ghana since the annual rain fall pattern has become very erratic.

Further evaluation need to be carried out on the core selection to identify trait-specific accessions that can be exploited for hybrid development as well as improvement in the landraces as well as variety development

The gene for downy mildew susceptibility needs to be identified together with the race of pathogen responsible for disease initiation in future breeding work.

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Appendices

Appedix 1: Pearl millet germplasm collection sheet

FIELD DATA COLLECTION SHEET

1. Collection Number:.....
2. Date of collection:.....
3. Region:.....
4. District:.....

5. Precise Locality (Village):.....

6. GPS:.....

7. Sample Source: Field....., Farmer seed sample....., Market.....

8. Ethnic group:.....

9. Local Name(s):.....

10. Farmer's source of seed:.....

11. Framer's Desirable Traits: .....

.....

12. Reasons for its cultivation:.....

..... 13. Uses:.....

.....

14. Maturity: Early ....., Medium....., Late.....

15. Month of planting:.....Month of harvesting.....

16 Mode of cultivation: Sole....., Mixture....., other crops.....

.....

17. Climatic Code (rainfall): A= Assured..... E= Erratic.....

18. Common diseases problems:.....

19. Common Insects problems:.....

20. Any problems with the variety:.....

.....

21. Any other information:.....

.....

Appedix II: Passport (ethno-botanical) data on Pearl millet accessions collected in three Regions of Northern Ghana, 2011

ACCESSION No.*	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/001	Upper West	Sisala East	Bassisan	Sissala	Mimpuna	*Pennisetum*	*glaucum*	Striga resistant, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/002	Upper West	Sisala West	Sorbelle	Sissala	Mipulima	*Pennisetum*	*glaucum*	Striga resistant, poor soils, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/003	Upper West	Sisala West	Pulima	Sissala	Mipulima	*Pennisetum*	*glaucum*	Striga resistant, birds resistance, poor soils, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/004	Upper West	Sisala West	Pulima	Sissala	Mipulima	*Pennisetum*	*glaucum*	Striga resistant, poor soil, drought toleranct	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/005	Upper West	Sisala East	Chinchang	Sissala	Mipulima	*Pennisetum*	*glaucum*	Striga resistant, poor soil, bird resistance, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/006	Upper West	Sisala East	Tafiesi	Sissala	Mipulima	*Pennisetum*	*glaucum*	Striga resistant, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/007	Upper West	Sisala West	Zini	Sissala	Mipulima	*Pennisetum*	*glaucum*	Marginal/Poor soils, drought toleranct	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/008	Upper West	Sisala West	Piina	Sissala	Mipulima	*Pennisetum*	*glaucum*	Striga resistant, drought toleranct	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/009	Upper West	Lawra	Brutu	Dagaaba	Zea	*Pennisetum*	*glaucum*	Lateness,	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/010	Upper West	LambuseiKarni	Hapan-Hamile	Sissala	Zea	*Pennisetum*	*glaucum*	poor soils and striga fields	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/011	Upper West	LambuseiKarni	Hapan-Hamile	Sissala	Mipulima	*Pennisetum*	*glaucum*	poor soils and striga fields	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/012	Upper West	Nadowle	Banu	Dagaaba	Mipulima	*Pennisetum*	*glaucum*	Striga resistance, Drought tolerance	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/013	Upper West	Lawra	Kumasa	Dagaaba	Zea	*Pennisetum*	*glaucum*	Marginal/Poor soils, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity

SARMIL 11/014	Upper West	Lawra	Kuwari-Eremon	Dagaaba	Zea	*Pennisetum*	*glaucum*	Lateness, striga resistance	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/015	Upper West	Jerapa	Kuncheri	Dagaaba	Zea	*Pennisetum*	*glaucum*	Striga and birds due to lateness	Late	Sole or intercropping with legumes	Declining Poor soil fertillity

Appendix II Cont.

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/016	Upper West	Jerapa	Wuli	Dagaaba	Zea	*Pennisetum*	*glaucum*	Good for poor soils	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/017	Upper West	Lawra	ChabatanBabile	Dagaaba	Zea	*Pennisetum*	*glaucum*	Lateness (can be harvested later)	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/018	Upper West	Lawra	ChabatanBabile	Dagaaba	Zea	*Pennisetum*	*glaucum*	Lateness (can be harvested later)	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/019	Upper West	Nadowle	Dakpaa	Dagaaba	Zea	*Pennisetum*	*glaucum*	Marginal/Poor soils, drought tolerant	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/020	Upper West	Nadowle	Kaleo	Dagaaba	Zea	*Pennisetum*	*glaucum*	Poor soils and striga fields	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/021	Upper West	Wa East	Issa-Sabogi	Dagaaba	Zea	*Pennisetum*	*glaucum*	Late planting and harvesting	Late	Sole or intercropping with legumes	Declining Poor soil fertillity
SARMIL 11/022	Upper West	Wa East	Funsi	Sissala	Mipulima	*Pennisetum*	*glaucum*	Drought tolerance and hardy	Late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/023	Upper West	Wa West	Siriyiri	Waala	Zea	*Pennisetum*	*glaucum*	Late maturity and harvesting	Late	Sole or intercrop with local beans	Declining Poor soil fertillity
SARMIL 11/024	Upper West	Wa West	Siela	Waala	Zea	*Pennisetum*	*glaucum*	good for poor soils, late harvesting	Late	Sole or intercrop with local beans	Declining Poor soil fertillity
SARMIL 11/025^{+}	Upper West	Wa Central	Bihee-Busa	Waala	Zea	*Pennisetum*	*glaucum*	Marginal/Poor soils, drought tolerant	Late	Sole or intercrop with local beans	Declining Poor soil fertillity

SARMIL 11/026	Upper West	Wa Central	Tampaala	Dagaaba	Zea	*Pennisetum*	*glaucum*	Lateness and drought tolerance	Late	Sole or intercrop with local beans	Declining Poor soil fertillity
SARMIL 11/027	Northern	Sawla-Tuna-Kalba	Gindabito	Lobi	Jea	*Pennisetum*	*glaucum*	Poor and exhusted fields	Late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/028	Northern	Sawla-Tuna-Kalba	Gindabuo	Gonja/Lobi	Jea	*Pennisetum*	*glaucum*	Earliness and good for late planting	Early	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/029	Northern	Sawla-Tuna-Kalba	Gindabuo	Gonja/Lobi	Jea	*Pennisetum*	*glaucum*	Earliness and good for late planting	Early	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/030	Northern	Sawla-Tuna-Kalba	Daniwuur	Gonja/Lobi	Jea	*Pennisetum*	*glaucum*	marginal/Poor soils	late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/031	Northern	Bole	Bodi	Brifo	Jea	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity

Appendix II cont.

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/032	Northern	Bole	Bodi	Brifo	Jea	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity
SARMIL 11/033	Northern	Bole	Mandari	Safalba/Vagla	mipuna	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity
SARMIL 11/034^{+}	Northern	Bole	Mandari	Safalba/Vagla	mipuna	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity
SARMIL 11/035	Northern	Bole	Bale	Brifo	Jea	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity
SARMIL 11/036	Northern	Bole	Gole	Brifo/Lobi	Jea	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity
SARMIL 11/037	Northern	Bole	Gole	Brifo/Lobi	Jea	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or intercropping with Sorghum and Groundnut	Declining Poor soil fertillity
SARMIL 11/038	Northern	Sawla-Tuna-Kalba	Nyanga	Brifo	Jea	*Pennisetum*	*glaucum*	Exhusted yam fields	late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity

SARMIL 11/039	Northern	West Gonja	Grupe	Gonja	Oduribi	*Pennisetum*	*glaucum*	Marginal soils	late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/040	Northern	West Gonja	Nabori	Gonja	Oduribi	*Pennisetum*	*glaucum*	Marginal soils	late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/041	Northern	West Gonja	Soalepe	Gonja	Oduribi	*Pennisetum*	*glaucum*	Poor soils and lateness	late	Sole or Intercropping in Yam farms	Declining Poor soil fertillity
SARMIL 11/042	Northern	Savelugu	Kanshegu	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga resistance/tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/043	Northern	Savelugu	Tigu	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga resistance/tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/044	Northern	Savelugu	Boting-bila	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Good for Marginal soils	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/045	Northern	Tolon-Kumbungu	Saakuba	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/046	Northern	Tolon-Kumbungu	Nyoring	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/047	Northern	Tolon-Kumbungu	Nyoring	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity

Appendix II cont.

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/048	Northern	Tolon-Kumbungu	Jagriguyili	Dagomba	Za-youli	*Pennisetum*	*glaucum*	lateness and good for poor soils	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/049	Northern	Central Gonja	Sankpagda	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Grow on poor soils	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/050	Northern	Central Gonja	Fufulsu	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Good for bush farms	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/051	Northern	Central Gonja	Bilisikura	Dagomba	Za-youli	*Pennisetum*	*glaucum*	No input needed like yam	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/052	Northern	Central Gonja	Mankpang	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga tolerance and lateness	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/053	Northern	Tamale Central	Nangbanga-Yipala	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/054	Northern	East Gonja	Masaka	Gonja	Oduribi	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/055[£]	Northern	Nanumba South	Kabliya	Nanumba	Za-peliga	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/056	Northern	Nanumba North	Kpabi	Nanumba	Za-peliga	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/057	Northern	Nanumba North	Gulnyansi	Nanumba	Za-peliga	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/058	Northern	Yendi	Zang	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Late maturity and harvesting	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/059	Northern	Yendi	Zang	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Late maturity and harvesting	late	Sole or intercropping with	Declining Poor soil fertillity

Appendix II cont.

SARMIL 11/060	Northern	Zabzugu	Mantili	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Good for bush farms	late	Yam, Groundnut, Sorghum Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/061+	Northern	Zabzugu	Bukukolimbe	Dagomba	Za-youli	*Pennisetum*	*glaucum*	resistance to striga	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/062	Northern	Yendi	Sakpegu	Dagomba	Za	*Pennisetum*	*glaucum*	Good for Marginal soils	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/063	Northern	Saboba	Wandamdo	Konkomba	Eyu	*Pennisetum*	*glaucum*	Good for rocky areas	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/064	Northern	Saboba	Nankpando	Konkomba	Eyu	*Pennisetum*	*glaucum*	Good for rocky areas	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/065	Northern	Chereponi	Achuma	Chekosi	Nyakpe	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/066	Northern	Chereponi	Tambong	Chekosi	Nyakpe	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/067	Northern	Gushegu	Wanfugu	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Striga resistance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/068	Northern	Karaga	Shebo	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Lateness for harvesting	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/069	Northern	Gushegu	Gae	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Lateness for harvesting	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/070	Northern	Karaga	Kariboyili	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Lateness for harvesting	late	Sole or intercropping with	Declining Poor soil fertillity

Appendix II cont.

										Yam, Groundnut, Sorghum	
SARMIL 11/071£	Northern	Karaga	Kariboyili	Dagomba	Za-youli	*Pennisetum*	*glaucum*	Escape bird attack	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/072	Northern	East Mamprushi	Nyingari	Mamprushi	Za	*Pennisetum*	*glaucum*	Good for marginal fields	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/073	Northern	West Mamprushi	Wung-NabFungu	Mamprushi	Za	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/074	Northern	West Mamprushi	Wungu	Mamprushi	Za	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/075	Northern	West Mamprushi	Sariba	Mamprushi	Za	*Pennisetum*	*glaucum*	Drought tolerance	late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/076	Northern	West Mamprushi	Duu	Mamprushi	Za	*Pennisetum*	*glaucum*	Earliness and poor fields	Early	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/077	Northern	West Mamprushi	Duu	Mamprushi	Za	*Pennisetum*	*glaucum*	Earliness and poor fields	Early	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/078	Northern	West Mamprushi	Duu	Mamprushi	Za	*Pennisetum*	*glaucum*	Drought tolerance	Late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/079	Northern	Bunkpurugu-Yonyuo	Kauk	Bimobas	Dee	*Pennisetum*	*glaucum*	Very Early maturing	Early	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/080	Northern	Bunkpurugu-Yonyuo	Kauk	Bimobas	Dee	*Pennisetum*	*glaucum*	Marginal soils	Late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/081£	Northern	Bunkpurugu-Yonyuo	Yunyoo	Bimobas	Dee	*Pennisetum*	*glaucum*	Short and Early	Early	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity

Appendix II cont.

SARMIL 11/082	Northern	Bunkpurugu -Yonyuo	Yunyoo	Bimobas	Dee	*Pennisetum*	*glaucum*	Seed colour-good for Tuo	Late	Sole or intercropping with Yam, Groundnut, Sorghum	Declining Poor soil fertillity
SARMIL 11/083	Upper East	Talensi-Nabdam	Shia	Talensi	Naara	*Pennisetum*	*glaucum*	Earliness	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/084	Upper East	Talensi-Nabdam	Shia	Talensi	Za	*Pennisetum*	*glaucum*	Marginal fields	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/085	Upper East	Talensi-Nabdam	Tindongo	Talensi	Naara	*Pennisetum*	*glaucum*	Does well by the house	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/086	Upper East	Talensi-Nabdam	Tindongo	Talensi	Za	*Pennisetum*	*glaucum*	Drought tolerance	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/087	Upper East	Bolgatanga	Sirigu	Frafra	Za	*Pennisetum*	*glaucum*	Drought tolerance	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/088	Upper East	Bolgatanga	Sirigu	Frafra	Naara	*Pennisetum*	*glaucum*	Respond to manure very fast	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/089	Upper East	Bolgatanga	Gowrie	Frafra	Naara	*Pennisetum*	*glaucum*	can withstand birds and lodging	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/090	Upper East	Bolgatanga	Gowrie	Frafra	Za	*Pennisetum*	*glaucum*	No bird attack-clean seeds	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity

Appendix II Cont.

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/091	Upper East	Bolgatanga	Gowrie	Frafra	Za	*Pennisetum*	*glaucum*	Striga tolerance	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/092	Upper East	Bongo	Sagbo (Anafo-bisi)	Boosi	Naara	*Pennisetum*	*glaucum*	Earliness	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/093+	Upper East	Bongo	Sagbo (Anafo-bisi)	Boosi	Za	*Pennisetum*	*glaucum*	Good for rocky areas	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/094	Upper East	Bongo	Feo	Boosi	Naara	*Pennisetum*	*glaucum*	Earliness	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/095	Upper East	Bongo	Feo	Boosi	Za	*Pennisetum*	*glaucum*	Good for poor soils	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/096	Upper East	KassenaNankana East	sirigu-Dazongo	Nankani	Naara	*Pennisetum*	*glaucum*	Ealiness, poor soils, good Tuo	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/097	Upper East	KassenaNankana East	Sirigu-Dazongo	Nankani	Naara	*Pennisetum*	*glaucum*	Earliness, Poor soil	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/098	Upper East	KassenaNankana East	sirigu-Dazongo	Nankani	Za	*Pennisetum*	*glaucum*	Less bird and insect damage	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/099	Upper East	KassenaNankana East	Sirigu-Dazongo	Nankani	Za	*Pennisetum*	*glaucum*	Less bird and insect damage	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/100	Upper East	KassenaNankana West	Nania	Kassim	Chaara	*Pennisetum*	*glaucum*	Striga resistance	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/101	Upper East	KassenaNankana West	Nania	Kassim	Mimpuna	*Pennisetum*	*glaucum*	Striga resistance	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/102	Upper East	KassenaNankana West	ChianaSaboro	Kassim	Chaara	*Pennisetum*	*glaucum*	All types of fields	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/103	Upper East	KassenaNankana West	ChianaSaboro	Kassim	Mimpuna	*Pennisetum*	*glaucum*	All types of fields	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity

SARMIL 11/104	Upper East	Builsa	Wiaga	Builsa	Naara	*Pennisetum*	*glaucum*	All types of fields	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/105	Upper East	Builsa	Wiaga	Builsa	Naara	*Pennisetum*	*glaucum*	All types of fields	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity

Appendix II Cont.

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/106	Upper East	Builsa	Wiaga	Builsa	Za-peala	*Pennisetum*	*glaucum*	All types of fields	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/107	Upper East	Builsa	KanjagaGobsa	Builsa	Naara	*Pennisetum*	*glaucum*	Good response to manure and ash	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/108	Upper East	Builsa	KanjagaGobsa	Builsa	Za-peala	*Pennisetum*	*glaucum*	Lateness and strong stalks	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/109	Upper East	Kassena-Nanka East	Doba	Nankani	Naara	*Pennisetum*	*glaucum*	Does not suufer when intercropped	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/110	Upper East	Kassena-Nanka East	Doba	Nankani	Za	*Pennisetum*	*glaucum*	Does not suufer when intercropped	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/111	Upper East	Garu-Tempane	Denugo	Kusal-Agole	Naara	*Pennisetum*	*glaucum*	Very Early maturing	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/112	Upper East	Garu-Tempane	Denugo	Kusal-Agole	Za	*Pennisetum*	*glaucum*	Marginal and bush farms	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/113	Upper East	Garu-Tempane	Kukazuli	Kusal-Agole	Naara	*Pennisetum*	*glaucum*	Earliness	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/114	Upper East	Garu-Tempane	Kukazuli	Kusal-Agole	Za	*Pennisetum*	*glaucum*	Striga and drought tolerance	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/115	Upper East	Bawku Municupal	TeraagoPusiga	Kusal-Agole	Naara	*Pennisetum*	*glaucum*	Good Food Quality	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/116	Upper East	Bawku Municupal	TeraagoPusiga	Kusal-Agole	Za	*Pennisetum*	*glaucum*	Good Food Quality	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/117	Upper East	Bawku Municupal	TeraagoPusiga	Kusal-Agole	Za	*Pennisetum*	*glaucum*	Good Food Quality	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity

SARMIL 11/118	Upper East	Bawku Municipal	Tansia	Kusal-Agole	Za	*Pennisetum*	*glaucum*	Poor soils	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/119	Upper East	Bawku Municipal	Tansia	Kusal-Agole	Naara	*Pennisetum*	*glaucum*	Good relay with Cowpea	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/120	Upper East	Bawku Municipal	Googo	Kusal-Agole	Naara	*Pennisetum*	*glaucum*	Earliness	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/121	Upper East	Bawku Municipal	Googo	Kusal-Agole	Za	*Pennisetum*	*glaucum*	Strong Stalks and good yields	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/122	Upper East	Bawku West	Kusanaba	Kusal-Toende	Naara	*Pennisetum*	*glaucum*	Less damage by insects, no birds	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity

Appendix II Cont.

ACCESSION No.	Region	Municipal/ District	Location/Community	Ethnic Group	Local name	Genus	Species	Desirable Trait	Maturity	Mode of Cultivation	Problems
SARMIL 11/123	Upper East	Bawku West	Kusanaba	Kusal-Toende	Za	*Pennisetum*	*glaucum*	Drought tolerance and hardy	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/124	Upper East	Bawku West	Kusanaba	Kusal-Toende	Za	*Pennisetum*	*glaucum*	Drought tolerance and hardy	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/125	Upper East	Kassena-Nankan West	Banyono	Kassim	Chaara	*Pennisetum*	*glaucum*	Hairy spikes that prevent birds	Early	Intercropping with Sorghum and local beans	Declining Poor soil fertillity
SARMIL 11/126	Upper East	Kassena-Nankan West	Banyono	Kassim	Mimpuna	*Pennisetum*	*glaucum*	Good tillering and drought tolerance	Late	Intercropping with Sorghum and local beans	Declining Poor soil fertillity

*: the names were derived from SARI, Millet, year and sample number (SARMIL 11/), £: Accessions that failed to germinate, + Accessions not included in genotyping

Appendix III: Polymorphic microsatellite primers and their sequence (Forward and Reverse)

	Primer	Forward Sequence (5′3′ –)	Reverse Sequence (5′3′ –)
1	XPsmp2246	**5′**-CGGATGCTAAATTAACCGAAGC-**3′5** ′ -CCAGCTTGCTTCTGTTGCGTTC-**3′**	
2	M13_Xpsmp2077	GCCAATATTATTCCCAAGTGAACA	CTCTTGGTTGCATATCTTTCTTTT
3	Xpsmp2276	TGTGGCAATTACGGTCGAGC	CTACCTCTATCTTACTTCACC
4	Xctm12	GTTGCAAGCAGGAGTAGATCGA	CGCTCTGTAGGTTGAACTCCTT
5	Xicmp3027	ACACCATCACCGACAACAAA	AGTGACCTGGGGTACAGACG
6	Xpsmp2233	TGTTTTCTCCTCTTAGGCTTCGTTC	TGTTTTCTCCTCTTAGGCTTCGTTC
7	Xpsmp2085	GCACATCATCTCTATAGTATGCAG	AAAAGCATCCTCAAATACCCAT
8	Xpsmp2248	TCTGTTTGTTTGGGTCAGGTCCTTC	CGAATACGTATGGAGAACTGCGCATC
9	Xicmp3050	ATGTCCAGTGTTGACGGTGA	CGGGGAAGAGACAGGCTACT
10	Xicmp3032	AGGTAGCCGAGGAAGGTGAG	CAACAGCATCAAGCAGGAGA
11	Xpsmp2232	TGTTGTTGGGAGAGGGTATGAG	CTCTCGCCATTCTTCAAGTTCA
12	Xpsmp2249	CAGTCTCTAACAAACAAACACGGC	GACAGCAACCAACTCCAAACTCCA
13	Xpsmp2261	AATGAAAATCCATCCCATTTCGCC	CGAGGACGAGGAGGGCGATT
14	M13_Xpsmp2206	AGAAGAAGAGGGGGTAAGAAGGAG	AGCAACATCCGTAGAGGTAGAAG
15	Xpsmp2210	CAATGATGACCGTAATCTGGGTG	GGGCAAGATATGTGAAATCAAG
16	Xpsmp2270	AACCAGAGAAGTACATGGCCCG	CGACGAACAAATTAAGGCTCTC
17	Xpsmp2275	CCAGTGCCTGCATTCTTGGC3	GCATCGAATACTTCATCTCA
18	Xpsmp2277	GGAATGCTCATCCAATACCCTCC	CCAGGACTGATGAGGTGTGGC
19	Xpsmp2224	GGCGAAATTGGAATTCAGATTG	CGTAATCGTAGCGTCTCGTCTAA
20	Xicmp3002	CGAGCCGCCATAGTTGAC	TACACACACATTGCCACACG
21	Xpsmp2219	ACTGATGGAATCTGCTGTGGAA	GCCCGAAGAAAAGAGAACATAGAA

22	M13_Xpsmp2086	CGCTTGTTTTCCTTTCTTGCTGTT	CCTTCTCAGATCCTGTGCTTTCTT
23	M13_Xpsmp2030	ACCAGAGCTTGGAAATCAGCAC	CATAATGCTTCAAATCTGCCACAC
24	Xpsmp2045	TCATCTTCCCCTATCCGAAAC	ACTTGCCAATGCTATCTTCAC
25	Xpsmp2080	CAGAATCCCCACATCTGCAT	TGCAACTGAGCGAACATCAA
26	M13_Xpsmp2203	GAACTTGATGAGTGCCACTAGC	TTGTGTAGGGAGCAACCTTGAT
27	Xpsmp2222	TGGCTTCCAGACTAATCATCAC	TTATTTTAGCGGCGAGATTGAC
28	Xpsmp2068	CAATAACCAAACAAGCAGGCAG	CTTCACTCCCACCCTTTCTAATTC
29	Xpsmp2266	CAAGGATGGCTGAAGGGCTATG	TTTCCAGCCCACACCAGTAATC
30	Xpsmp2201	CCCGACGTTATGCGTTAAGTT	TCCATCCATCCATTAATCCACA
31	Xpsmp2208	GAAAGAGCAAACTGAACAATCCC	ACTTTGCCCTGGATGATCCTC
32	Xpsmp2227	ACACCAAACACCAACCATAAAG	TCGTCAGCAATCACTAATGACC
33	M13_Xctm10	GAGGCAAAAGTGGAAGACAG	TTGATTCCCGGTTCTATCGA
34	M13_Xpsmp2087	GGAACAGACTCCATACCTGAAA	TACCTGCCTGTGCTGTTAGT
35	M13_Xpsmp2090	AGCAGCCCAGTAATACCTCAGCTC	AGCCCTAGCGCACAACACAAACTC
36	M13_Xpsmp2273	AACCCCACCAGTAAGTTGTGCTGC	GATGACGACAAGACCTTCTCTCC

Some forward primers are labelled with M13 tail which is 19 nucleotide sequence given below.

M13-

CACGACGTTGTAAAACGAC

Appendix IV-A: Summary of mean agronomic characterisation of Early-maturing group collected from Upper East, West and Northern Regions and planted at Manga Research Station, Bawku (Upper East)

treatment	Stands /plot	DM incid. at 30 days	DM incid. at 70 days	days to 50% boot	stover wt/plt (kg)	head length averag e (cm)	head girth (cm)	plant height averag e (cm)	thousan d seed wt (g)	average tillers/pla nt	average producti ve tillers/pl ant	Spike density	spike shape	seed colour	seed shape
SARMIL 076	15	17.1	49	41	0.18	16.42	7.96	153	8.85	6	4	5	1	5	5
SARMIL 077	18.25	10.1	37.9	37	0.205	15.58	7.82	149.2	12.21	6	5	3	1	5	5
SARMIL 079	18.75	9.4	24.9	38	0.187	16	8.24	141.5	9.62	6	4	5	1	5	1
SARMIL 083	4.5	0	45	39	0.23	18.17	7.85	147	11.05	6	4	3	1	5	5
SARMIL 085	15	8.3	46.6	41	0.235	17.25	7.61	175.8	9.27	6	6	5	1	5	4
SARMIL 088	14.25	10.6	53.8	42	0.274	15.92	8.06	160.8	9.84	8	5	5	1	5	1
SARMIL 089	16.75	29.2	63	41	0.298	17.08	8.45	162.2	9.65	6	4	5	1	5	1
SARMIL 092	13.25	7.5	35.4	42	0.56	15.67	9.22	141.5	9.66	7	4	3	1	5	4

SARMIL 094	17	8.3	44.5	39	0.271	18.08	8.6	163.8	9.11	4	4	5	1	5	1
SARMIL 096	12.75	18.7	59.4	45	0.253	18.33	7.5	158	10.23	7	4	5	5	5	4
SARMIL 097	12.75	16.3	59.6	40	0.387	24.67	7.72	163	10.67	6	3	5	1	5	5
SARMIL 100	19	12.5	36.7	40	0.333	20.33	8.8	170.2	9.85	5	4	5	1	5	4
SARMIL 102	18.75	8.3	11.9	41	0.313	19.83	8.3	174	9.74	6	3	5	1	5	5
SARMIL 104	20	7.9	27.1	38	0.34	18.25	8.09	161	12.11	7	7	5	1	5	5
SARMIL 105	17.5	8.1	28.1	40	0.266	19.33	7.74	161	9.84	6	4	5	1	5	5
SARMIL 107	18	13.8	23.1	41	0.334	21.25	8.79	171.5	11.6	5	4	5	1	4	1
SARMIL 109	15.25	14.4	48.2	43	0.403	22.67	8.06	174.5	10.02	7	4	5	1	5	5
SARMIL 111	17	13.4	37.6	42	0.225	15.33	8.87	160	10.82	6	4	3	1	5	5
SARMIL 113	15.5	13.5	44.7	39	0.274	15.92	9.52	157.2	11.66	7	6	3	1	6	5
SARMIL 115	16	14.2	35.9	43	0.41	18.92	8.82	154	11.1	5	4	3	1	5	5
SARMIL 119	19	8.3	38.2	40	0.249	16.83	8.53	155	11.06	6	5	5	1	5	5
SARMIL 120	18.5	2.8	32.3	40	0.293	17.92	8.97	156.8	10.83	6	4	3	1	5	5
SARMIL 122	18.5	18.2	49.3	40	0.294	17.67	8.67	158.8	10.89	5	4	5	1	6	1
SARMIL 125	14.5	0	23.2	40	0.31	21.92	8.56	166.2	9.69	5	3	5	5	5	5
Mean	16.07	11.3	39.8	40	0.297	18.31	8.364	159.8	10.39	6	4				
Lsd	5.077	19.25	21.41	5.5	0.208	4.12	1.02	18.92	2.89	2	2				

P (0.05)	<0.001	NS	<0.001	NS	NS	<0.001	0.006	0.015	NS	NS	NS
CV%	22.4	121.0	38.1	6.6	49.6	18.31	8.6	8.4	19.7	20.1	25.0
Se	3.56	12.64	15.17	2.65	0.15	2.92	0.72	13.41	2.05	1.15	1.04

Appendix IV-B: Summary of mean agronomic characterisation of medium-maturing group collected from Upper East, West and Northern Regions and planted at Manga Research Station, Bawku (Upper East)

treatment	Average Stands / plot	DM Incidence at 30 days	DM Incidence at 70 days	Days to 50% boot	Stover wt/plant (kg)	Average head length (cm)	Average head girth (cm)	Average plant height (cm)	Average tillers/ plant	Average productive tillers/ plant	Average thousand seed wt (g)	spike density	spike shape	seed colour	seed shape
SARMIL 001	17	6.51	14.6	90	0.927	22.2	8.9	364.8	7	4	10.02	5	1	4	4
SARMIL 002	11	15.63	51.8	79.5	1.538	26.9	6.4	322.7	8	6	9.87	5	1	4	4
SARMIL 003	15	11.56	29.4	84	0.965	29.45	7.25	326.3	8	6	9.96	5	5	3	5
SARMIL 004	17	15.2	18.8	78	0.875	29.25	8.25	376.4	7	5	11.25	5	1	1	5
SARMIL 005	18	5.77	7.7	74	0.985	29.45	7.9	330.8	7	5	10.68	5	5	4	4
SARMIL 006	13	8.11	45	80	0.83	26.8	6.6	349.2	7	4	8.4	5	1	3	5
SARMIL 007	18	2.78	9.4	78	1.738	21.5	8.45	362.6	6	5	8.2	5	1	4	5
SARMIL 008	18	5.97	15.8	80.5	1.188	21.85	8.13	367.7	7	5	9.47	5	1	4	4

SARMIL 009	17	17.06	17.1	80	1.055	23.25	8.75	325.7	7	5	9.46	5	1	3	1
SARMIL 010	17	0	0	78	0.96	24	8.63	394.5	8	6	10.41	5	1	4	4
SARMIL 011	18	13.71	13.2	75.5	0.908	23.05	7.85	345.6	6	5	8.88	5	5	4	1
SARMIL 013	19	9.98	27.9	81.5	1.297	21.62	8.08	347.4	8	6	10.23	5	1	5	5
SARMIL 014	18	6.82	21.3	78	1.188	20.85	7.98	362.3	8	6	8.81	5	1	4	1
SARMIL 015	16	9.58	30.9	80.5	1.885	23.95	10.43	317.3	8	6	9.42	5	1	5	5
SARMIL 016	18	1.92	7.1	79	1.135	21.35	8.7	342.1	6	4	8.37	5	5	5	4
SARMIL 017	19	5.54	32.9	82.5	1.262	25.15	8.4	339.4	6	5	7.25	5	1	4	5
SARMIL 018	18	13.6	28.2	78.5	1.075	25.75	8.75	356.2	7	5	7.71	5	1	3	1
SARMIL 043	16	2.63	35.5	89.5	1.073	22.4	9.68	365.3	8	6	9.29	5	1	5	5
SARMIL 044	15	2.27	40.9	99	1.025	18.2	6.8	319.8	7	5	5.66	5	1	5	1
SARMIL 045	15	8.69	27.5	97.5	1.09	22.22	9.48	387.3	9	5	8.38	5	5	4	5
SARMIL 049	19	11.53	25	98.5	1.14	20.5	8.65	353.3	10	6	10.23	5	1	4	4
SARMIL 051	16	16.88	25	96.5	1.07	20.8	8.43	352.5	7	4	10.06	5	1	5	5
SARMIL 053	14	4.77	59.1	92	0.8	19.45	8.35	326.7	11	5	8.91	3	1	5	5
SARMIL 059	18	1.79	13	92.5	1.018	21.3	8.5	359	7	4	8.21	5	1	5	5
SARMIL 062	17	17.95	29.2	97.5	0.93	23.11	8.9	349.8	6	4	8.05	5	1	4	4

SARMIL 063	17	10	41.7	99	0.685	18.5	8.13	349.3	8	5	7.99	5	1	4	4
SARMIL 065	16	3.85	11	93.5	1.115	26.9	9.28	347.2	10	6	7.8	5	1	5	5
SARMIL 066	19	12.22	29.4	97.5	0.738	22.5	8.88	337.2	8	6	8.71	5	1	5	4
SARMIL 067	14	11.11	27.8	92	0.878	19.95	8.43	349.3	9	6	8.85	3	1	1	5
SARMIL 068	14	1.92	11.5	94	0.917	21.4	9.13	331	10	6	9.11	3	1	1	4
SARMIL 070	15	1.56	14.9	100	0.838	19.75	8.6	355.5	8	5	9.01	3	1	4	5
SARMIL 078	14	10.56	33.3	93	1.19	23.7	8.68	345.4	8	4	9.48	3	1	3	5
SARMIL 080	14	3.82	9.8	97	0.788	23.75	8.93	338.6	9	6	12.07	5	1	5	4
SARMIL 082	18	6.98	25	94	0.965	21.6	11.93	346.7	9	6	9.81	3	1	5	5
SARMIL 087	13	3.85	17	81.5	0.923	27.22	9.63	310.8	8	5	9.78	5	1	3	4
SARMIL 090	15	10.19	6.1	74.5	0.92	24.57	7.25	294	7	6	9.72	5	1	3	1
SARMIL 091	18	8.63	17.2	68	0.675	24.8	9	306.8	6	5	10.23	5	1	3	5
SARMIL 093	13	9.32	19.4	75.5	1.157	21.3	7.68	276.2	7	6	8.91	5	1	5	5
SARMIL 095	16	14.02	34.3	73.5	0.805	26.95	8.08	322.9	6	4	10.45	5	1	5	5
SARMIL 098	18	8.75	27.5	84.5	1.62	26.95	8.5	359	8	6	9.36	5	1	3	4
SARMIL 099	11	0	18.8	77	0.748	25.9	7.9	313.9	6	5	8.21	5	1	4	5
SARMIL 101	17	1.47	2.9	84.5	0.64	25.7	7.28	351.3	8	6	8.8	5	5	1	1
SARMIL 103	17	5.51	34.1	90	0.993	24	9	356.2	7	5	9.79	5	1	4	5
SARMIL 106	19	5.63	6.3	81	1.038	24.12	8.05	346.1	7	6	10.48	5	1	4	1

SARMIL 110	17	3.33	6.1	78.5	1.262	27.3	7.88	319.7	9	8	11.42	5	1	4	1
SARMIL 112	17	0	10	86.5	1.325	28.5	9.6	308.8	10	8	9.92	5	1	4	5
SARMIL 114	17	3.97	34.1	78.5	1.275	24.65	8.45	305.2	9	8	10.49	5	1	1	5
SARMIL 116	16	7.25	36.6	85.5	1.408	25.5	8.93	368.3	7	5	13.22	5	1	4	1
SARMIL 117	19	6.32	16.9	73	1.12	29.65	6.95	352.9	6	5	10.11	5	5	1	5
SARMIL 118	19	12.37	28.2	85	1.45	24.6	7.89	373.1	9	6	10.01	5	5	4	4
SARMIL 121	20	1.39	19.4	77	1.16	23.8	9.1	337.3	9	7	11.71	3	1	4	5
SARMIL 123	18	16.35	70.9	82	0.95	23.9	7.8	348.8	9	7	9.09	5	1	4	1
SARMIL 124	19	9.94	28.6	81	1.04	23.95	7.45	325.3	8	5	9.23	3	1	4	4
SARMIL 126	12	0	14.3	82.5	0.898	23.45	7.25	310.6	7	6	9.49	5	1	5	4
Mean	16.29	7.47	23.9	84.81	1.064	23.87	8.4	341.3	7.43	5.22	9.45				
Lsd	5.9	14.96	36.31	11.558	0.674	5.26	1.43	46.32	3.233	2.696	2.82				
p (5%)	ns	ns	ns	<.001	ns	<.001	<.001	<.001	ns	ns	0.021				
CV%	25.8	143.3	75.9	6.8	45.2	15.8	12.2	9.7	21.7	25.7	21.4				
Se	4.19	10.71	18.1	5.76	0.48	3.76	1.02	33.16	1.61	1.34	2.02				

Appendix IV-C: Summary of mean agronomic characterisation of late-maturing group collected from Upper East, West and Northern Regions and planted at Manga Research Station, Bawku (Upper East)

treatment	Stands /plot	DM incid. at 30 days	DM incid. at 70 days	days to 50% boot	stover wt/plt (kg)	head length average (cm)	head girth (cm)	plant height average (cm)	thousand seed wt (g)	average tillers/plant	average productive tillers/plant	spike density	spike shape	seed colour	seed shape
SARMIL 012	20.75	7.29	32.8	116	0.687	17.17	9.55	282.2	8.15	7	2	3	1	4	5
SARMIL 019	18.25	2.79	21	103	0.655	22.87	9.4	299.2	9.55	7	2	5	1	5	5
SARMIL 020	19.5	1.25	3.6	111	0.83	22.75	9.58	362.7	9.49	8	5	5	1	5	5
SARMIL 021	16	0	11.7	111	0.695	23.32	8.98	328.7	9.5	8	4	5	1	4	5
SARMIL 022	16.12	7.88	21.4	106	0.602	22.15	9.18	328.2	8.76	7	3	5	1	4	5
SARMIL 023	18.75	8.54	18.9	110	0.545	20.35	8.88	317.7	8.57	7	3	5	1	5	5
SARMIL 024	17.5	4.76	18.1	110	0.565	21.42	9.85	339.2	8.19	7	2	5	1	4	1
SARMIL 025	15.5	10.56	20.1	113	0.77	21.25	9.43	324	7.21	6	2	5	1	4	5
SARMIL 026	20.25	10.23	19	106	0.62	21.35	8.83	294.2	8.7	6	4	5	1	5	4
SARMIL 027	15.5	15.57	21	109	0.535	22.15	8.68	328.7	8.62	10	5	5	1	5	5
SARMIL 028	17.25	0	21.2	109	0.842	22	9.38	345	8.33	7	3	5	1	5	5
SARMIL 029	17	1.56	8.8	116	0.527	21.4	9.18	352.7	6.6	11	4	5	1	5	5
SARMIL 030	13	2.27	24.7	120	0.65	21.15	9.35	343.7	7.05	9	5	5	1	5	5

SARMIL 031	14.75	1.47	10.7	116	0.747	22.32	8.53	324.7	6.71	5	1	5	1	5	5
SARMIL 032	16.75	10.06	26.7	122	0.627	19	9.98	334.5	8.59	8	3	5	1	4	5
SARMIL 033	14	0	21.3	123	0.622	23.82	9.88	340.5	7.65	11	3	5	5	5	5
SARMIL 034	15	2.08	16.8	118	0.847	21.07	8.85	326.5	8.45	9	6	5	1	4	4
SARMIL 035	16	5.04	18	121	0.61	21.75	8.08	334.7	7.5	11	4	5	1	4	5
SARMIL 036	19.25	5.08	13	116	0.68	21	8.15	329.7	7.64	8	4	5	5	5	5
SARMIL 037	16.5	4.17	12.2	115	0.675	20.25	8.63	314.5	6.54	8	5	5	1	4	5
SARMIL 038	13.25	14.05	35.7	115	1.167	18.5	10.65	303	9.25	6	3	3	1	4	5
SARMIL 039	15.75	9.8	27.9	121	0.707	22	7.2	312.5	6.41	9	3	5	1	5	5
SARMIL 040	11.75	16.51	35.6	121	0.705	23.17	9.15	315	6.03	12	3	5	5	4	5
SARMIL 041	13.5	6.35	37.3	106	0.575	19.75	8.38	297.2	4.53	9	2	3	1	4	4
SARMIL 042	11.25	10.71	33.6	106	1.137	18.42	8.08	272	7.63	7	2	3	1	5	5
SARMIL 046	19.25	2.7	35.4	112	0.685	21.67	9.53	309.2	6.96	7	5	5	1	4	4
SARMIL 047	16.5	8.61	24.5	109	0.817	22.6	9.83	314.2	9.09	9	4	5	1	3	5
SARMIL 048	13.5	3.57	22.1	101	0.725	21.17	8.78	350.5	8.1	7	4	5	1	5	4
SARMIL 050	19	10.78	25.4	108	0.405	18.15	7.25	312	6.56	8	3	5	1	4	4
SARMIL 052	20	15.56	25.7	109	0.947	20.57	8.6	320.2	7.04	7	3	5	1	4	5
SARMIL 054	15	15.03	35.1	111	0.667	18.6	9.05	301.5	5.65	7	3	5	1	5	5

SARMIL 056	14.5	8.69	44.1	114	0.497	19.6	7.8	263.5	5.88	11	5	5	1	4	4
SARMIL 057	15	9.82	47.9	119	0.882	20.25	8.85	302.5	8.52	7	3	5	1	4	4
SARMIL 058	13.75	2.78	21.5	101	0.672	18.32	8.05	314.7	7.38	8	4	5	1	4	4
SARMIL 060	14	23.81	21.3	105	0.595	19.92	8.88	280.7	5.46	6	3	5	1	4	5
SARMIL 061	15	5	32.7	108	1.13	19.15	8.88	278.7	5.69	7	3	5	1	4	5
SARMIL 064	17.5	4.32	31.8	103	0.48	20.82	8.58	291.7	6.85	7	4	5	1	1	5
SARMIL 069	20	6.45	21.8	101	0.812	20.92	8.68	347.7	8.83	6	4	3	1	5	5
SARMIL 071	13.25	25	39.9	104	0.695	23.92	9.35	317.7	9.37	8	4	5	1	1	5
SARMIL 072	17.25	4.7	18.6	105	0.462	20.25	9.35	306.2	9.63	7	4	5	1	1	5
SARMIL 073	9.5	0	25	108	1.167	22.6	8.9	332.2	7.15	11	5	3	1	1	5
SARMIL 074	16.5	9.99	16.4	107	1.19	22.17	8.95	309.7	6.83	6	4	5	1	1	5
SARMIL 084	16.25	9.03	32.3	103	0.94	22.42	9.7	325.7	9.35	11	7	5	1	4	5
SARMIL 086	16	7.78	25.8	114	0.892	23	9.1	343.7	9.09	8	4	5	1	4	1
SARMIL 108	16.75	3.23	10.7	105	0.882	24.25	11	368	9.22	8	4	3	1	3	5
Mean	16.04	7.4	24.2	110.61	0.737	21.13	9	318.7	7.74	7.78	3.39				
Lsd (5%)	5.36	15.33	26.64	13.861	0.564	3.57	1.7	49.75	2.299	2.775	2.476				
P (0.05)	0.009	NS	NS	0.05	NS	0.007	0.068	0.007	<0.001	<.001	ns				
CV%	24.9	148.1	78.7	6.2	55.4	14.3	16.9	11.2	23.1	17.7	36.2				
Se	3.98	10.96	19.05	6.88	0.40	2.99	1.49	35.6	1.76	1.38	1.23				

Key

	1	2	3	4	5	6	7	8	9
Spike density			Loose		Intermediate		Compact		
Spike shape	Cylindrical	Conical	Spindle	Club	Candle	Dumb-bell	Lanceolate	Oblanceolate	Globose
Seed colour	Ivory	Cream	Yellow	Grey	Deep grey	Deep brown	Brown	Purple	Purplish black
Seed shape	Obovate	Oblanceolate	Elliptical	Hexagonal	Globular				

Apeendix IV-D: Range and means of selected traits of the maturity groups*

	Early-maturing		Medium-maturing		Late-maturing		Overall
	Range	Mean	Range	Mean	Range	Mean	Mean
DM incid @ 30 days (%)	0 – 29	11.30	0 – 17.95	7.47	0 – 23.81	7.40	8.72
DM incid @ 70 days (%)	11.9 – 63.0	39.60	0 – 70.9	23.90	3.6 – 47.9	24.20	29.23
Average head girth (cm)	7. 50 – 9.22	8.36	6.40 – 11.93	8.40	7.2 – 10.65	9.00	8.59
Average head length (cm)	15.33 - 24.67	18.31	18.20 – 29.65	23.83	17.17 – 24.25	20.92	21.02
Average plant height (cm)	141.5 – 175.8	159.80	276.2 – 394.5	341.30	263.5 – 368	318.50	273.2
Stover yield (kg) plant^{-1}	0.18 – 0.56	0.30	0.64 – 1.89	1.064	0.41 – 1.19	0.73	0.698
Thousand seed weight (g)	8.85 – 12.21	10.39	5.66 – 12.07	9.45	4.53 -9.63	7.64	9.16
Average total tillers plant^{-1}	4 – 8	6.00	6 – 11	7.00	5 – 12	8.00	7
Average productive tillers plant^{-1}	3 – 7	4.00	4 – 8	5.00	1 – 7	3.00	4
Days to 50% booting	37 – 45	40.00	68 – 100	84.81	101 – 123	110.61	78.47
Plant stand plot^{-1}	4.5 -20	16.07	11 – 20	16.29	9.5 – 20.75	15.98	16.11

* Data is based on a study of 123 accessions grown in a replicated plot at Manga in 2011

Appendix V- E: Genetic diversity analysis using 36 polymorphic microsatellite primers in 24 Early-maturity Pearl millet accessions

Marker	Major Allele Frquency	Allele No	Expected Heterozygosity	Observed Heterozygosity	PIC
XPsmp2246	0.452	3.0 4.0	0.622	0.238	0.544
M13_Xpsmp2077	0.886	6.0 7.0	0.210	0.136	0.202
Xpsmp2276	0.364	5.0 6.0	0.747	0.455	0.707
Xctm12	0.304	5.0 4.0	0.768	0.217	0.732
Xicmp3027	0.333	5.0 7.0	0.746	0.333	0.704
Xpsmp2233	0.354	5.0	0.722	0.167	0.674
Xpsmp2085	0.646	3.0	0.528	0.417	0.481
Xpsmp2248	0.477	10.0	0.581	0.455	0.491
Xicmp3050	0.750	4.0	0.414	0.364	0.388
Xicmp3032	0.500	11.0	0.669	0.304	0.627
Xpsmp2232	0.500	8.0 3.0	0.640	0.368	0.580
Xpsmp2249	0.947	7.0 3.0	0.101	0.105	0.099
Xpsmp2261	0.263	4.0 5.0	0.821	0.526	0.798
M13_Xpsmp2206	0.605	7.0 7.0	0.560	0.421	0.503
Xpsmp2210	0.250	5.0 6.0	0.855	0.458	0.840
Xpsmp2270	0.500	8.0	0.699	0.208	0.672
Xpsmp2275	0.646	3.0	0.503	0.292	0.435
Xpsmp2277	0.396	14.0	0.745	0.458	0.709
Xpsmp2224	0.500	9.0	0.623	0.348	0.552
Xicmp3002	0.479	3.0	0.648	0.375	0.586
Xpsmp2219	0.792	10.0	0.358	0.250	0.338
M13_Xpsmp2086	0.500	3.0	0.692	0.167	0.661
M13_Xpsmp2030	0.524	12.0	0.656	0.333	0.617
Xpsmp2045	0.391	4.0 8.0	0.715	0.478	0.666
Xpsmp2080	0.313	7.0	0.787	0.188	0.756
M13_Xpsmp2203	0.396	**6.1**	0.766	0.375	0.738
Xpsmp2222	0.792		0.348	0.167	0.316
Xpsmp2068	0.152		0.905	0.478	0.897
Xpsmp2266	0.239		0.836	0.435	0.816
Xpsmp2201	0.396		0.643	0.417	0.567
Xpsmp2208	0.500		0.709	0.500	0.688
Xpsmp2227	0.688		0.468	0.542	0.411
M13_Xctm10	0.119		0.908	0.429	0.901
M13_Xpsmp2087	0.524		0.622	0.476	0.561
M13_Xpsmp2090	0.413		0.772	0.174	0.750
M13_Xpsmp2273	0.344		0.779	0.063	0.749
Mean	**0.479**		**0.644**	**0.337**	**0.604**

Appendix V- diversity analysis using 36 p

M: Genetic olymorphic microsatellite primers in 54 Medium-maturity Pearl millet accessions

Marker	Major Allele Frquency	Allele No	Expected Heterozygosity	Observed Heterozygosity	PIC

Appendix V- diversity analysis using 36 p

XPsmp2246	0.698	3.0 4.0	0.443	0.313 0.375
M13_Xpsmp2077	0.948	8.0 7.0	0.100	0.083 0.098
Xpsmp2276	0.385	4.0 7.0	0.748	0.396 0.712
Xctm12	0.471	5.0 5.0	0.718	0.196 0.688
Xicmp3027	0.337	4.0 5.0	0.731	0.673 0.681
Xpsmp2233	0.327	7.0 4.0	0.780	0.102 0.749
Xpsmp2085	0.588	9.0	0.587	0.353 0.539
Xpsmp2248	0.725	6.0	0.436	0.412 0.396
Xicmp3050	0.643	11.0	0.473	0.388 0.379
Xicmp3032	0.602	15.0	0.572	0.347 0.523
Xpsmp2232	0.388	4.0	0.740	0.286 0.701
Xpsmp2249	0.833	10.0	0.288	0.167 0.263
Xpsmp2261	0.313	4.0 3.0	0.797	0.521 0.769
M13_Xpsmp2206	0.635	7.0 8.0	0.561	0.354 0.531
Xpsmp2210	0.240	7.0	0.860	0.327 0.845
Xpsmp2270	0.170	10.0	0.899	0.520 0.890
Xpsmp2275	0.674	10.0	0.459	0.370 0.380
Xpsmp2277	0.363	9.0	0.767	0.451 0.735
Xpsmp2224	0.637	4.0	0.531	0.431 0.478
Xicmp3002	0.856	19.0	0.254	0.212 0.233
Xpsmp2219	0.423	9.0 2.0	0.655	0.462 0.593
M13_Xpsmp2086	0.394	9.0	0.744	0.192 0.708
M13_Xpsmp2030	0.745	3.0	0.428	0.143 0.410
Xpsmp2045	0.309	11.0	0.789	0.319 0.760
Xpsmp2080	0.321	5.0	0.807	0.308 0.784
M13_Xpsmp2203	0.261	11.0	0.800	0.543 0.771
Xpsmp2222	0.402	3.0	0.685	0.510 0.624
Xpsmp2068	0.122	**7.0**	0.927	0.408 0.922
Xpsmp2266	0.340		0.779	0.520 0.748
Xpsmp2201	0.981		0.038	0.038 0.037
Xpsmp2208	0.490		0.697	0.392 0.665
Xpsmp2227	0.837		0.279	0.173 0.249
M13_Xctm10	0.190		0.885	0.340 0.874
M13_Xpsmp2087	0.388		0.661	0.531 0.593
M13_Xpsmp2090	0.398		0.781	0.347 0.758
M13_Xpsmp2273	0.711		0.449	0.111 0.402
Mean	**0.504**		**0.615**	**0.340 0.580**

L: Genetic olymorphic microsatellite primers in 45 Late-maturity Pearl millet accessions

Appendix V- diversity analysis using 36 p

Marker	Major Allele Frquency	Allele No	Expected Heterozygosity	Observed Heterozygosity	PIC
XPsmp2246	0.536	3.0	0.589	0.405	0.514
M13_Xpsmp2077	0.915	3.0	0.158	0.146	0.149
Xpsmp2276	0.583	7.0	0.607	0.381	0.570
Xctm12	0.402	10.0	0.764	0.366	0.737
Xicmp3027	0.345	4.0	0.734	0.500	0.685
Xpsmp2233	0.288	6.0	0.759	0.250	0.718
Xpsmp2085	0.573	4.0	0.596	0.463	0.543
Xpsmp2248	0.744	5.0	0.419	0.317	0.389
Xicmp3050	0.610	3.0	0.502	0.415	0.407
Xicmp3032	0.634	5.0	0.539	0.463	0.490
Xpsmp2232	0.375	5.0	0.708	0.450	0.655
Xpsmp2249	0.847	3.0	0.268	0.250	0.248
Xpsmp2261	0.250	12.0	0.833	0.476	0.814
M13_Xpsmp2206	0.538	7.0	0.652	0.575	0.616
Xpsmp2210	0.333	9.0	0.802	0.595	0.777
Xpsmp2270	0.226	15.0	0.865	0.310	0.852
Xpsmp2275	0.769	3.0	0.361	0.205	0.304
Xpsmp2277	0.595	7.0	0.598	0.310	0.563
Xpsmp2224	0.500	5.0	0.627	0.585	0.561
Xicmp3002	0.821	3.0	0.301	0.262	0.268
Xpsmp2219	0.381	5.0	0.681	0.571	0.619
M13_Xpsmp2086	0.463	9.0	0.727	0.171	0.700
M13_Xpsmp2030	0.702	7.0	0.486	0.429	0.465
Xpsmp2045	0.375	8.0	0.753	0.575	0.717
Xpsmp2080	0.350	10.0	0.812	0.533	0.793
M13_Xpsmp2203	0.325	7.0	0.795	0.600	0.767
Xpsmp2222	0.488	4.0	0.647	0.512	0.586
Xpsmp2068	0.146	16.0	0.915	0.585	0.908
Xpsmp2266	0.317	7.0	0.758	0.732	0.718
Xpsmp2201	0.964	2.0	0.069	0.071	0.067
Xpsmp2208	0.476	9.0	0.703	0.463	0.669
Xpsmp2227	0.845	3.0	0.268	0.262	0.243
M13_Xctm10	0.250	13.0	0.858	0.300	0.844
M13_Xpsmp2087	0.447	5.0	0.651	0.500	0.586
M13_Xpsmp2090	0.345	11.0	0.803	0.381	0.781
M13_Xpsmp2273	0.629	5.0	0.549	0.286	0.503
Mean	**0.511**	**6.7**	**0.616**	**0.408**	**0.578**