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Pearl Millet (*Pennisetum glaucum* L.) Hybrid Breeding in West Africa Towards High Productivity and Grain Iron (Fe) and Zinc (Zn) for Adaptation to Climate Change and Human Nutrition.

A THESIS

IN THE RURAL POLYTECHNIC INSTITUTE OF TRAINING AND APPLIED RESEARCH IN PARTNERSHIP WITH THE WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE (WASCAL), SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN CLIMATE CHANGE AND AGRICULTURE OF THE UNIVERSITY OF SCIENCES, TECHNIQUES AND TECHNOLOGIES OF BAMAKO (USTTB)

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DEDICATION

Dedicated To my lovely family and all my descendants yet to come;
my father Mr. HASSANE Abdou and my mother Ms IBRAHIM Fati.

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For those not mentioned be sure your contribution is not forgotten.

To all, I say thank you.

DECLARATION

I, HASSANE Zakari, declare successful completion of Ph.D. thesis work on **“Pearl Millet (*Pennisetum glaucum* L.) Hybrid Breeding in West Africa Towards High Productivity and Grain Iron (Fe) and Zinc (Zn) for Adaptation to Climate Change and Human Nutrition”,** under the supervision of Dr Prakash Irappa Gangashetty. I also declare that

1. This thesis, except where otherwise indicated, is my original development.
2. It has not been submitted to any university for any degree or examination.
3. This thesis does not contain other persons’ data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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HASSANE Zakari

CERTIFICATE

This is to certify that Mr Hassane Zakari has successfully completed his Ph.D. thesis research on "**Pearl Millet (*Pennisetum glaucum* L.) Hybrid Breeding in West Africa Towards High Productivity and Grain Iron (Fe) and Zinc (Zn) for Adaptation to Climate Change and Human Nutrition",** under my supervision at ICRISAT, Niamey, Niger. This is his original work and is not submitted to any university for the award of the degree. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

Dr Prakash Irappa Gangashetty

LIST OF ACRONYMS AND ABBREVIATIONS

AMMI: Additive Main Effects and Multiplicative Interaction

ASV: AMMI Stability Value

BPH: Better Parent Heterosis

CA: Combining Ability

Cm: Centimeter

CMS: Cytoplasmic Male Sterility

Fe: Iron

GCA: General Combining Ability

ICMA: ICRISAT Millet A-line

ICMB: ICRISAT Millet B-line

ICMR: ICRISAT Millet R-line

ICMV: ICRISAT Millet Variety

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

Kg: Kilograms

mg: Milligrams

MPH: Mid-Parent Heterosis

OPV: Open Pollinated Variety

SCA: Specific Combining Ability

SCH: Single Cross Hybrids

SH: Standard Heterosis

SI: Stability Index

TCH: Top Cross Hybrids

WA: West Africa

Zn: Zinc

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RESUME

Le mil (*Pennisetum glaucum* L.), sixième céréale au monde, est connu comme une culture intelligente face au climat en raison de sa tolérance à la sécheresse, à la chaleur, à la salinité du sol, à la faible fertilité des sols et à sa capacité à amortir des conditions environnementales variées. Le changement climatique et les contraintes écologiques de production devraient accroître les défis actuels auxquels l'agriculture est confrontée pour assurer la sécurité alimentaire future de la population croissante en Afrique de l'Ouest (AO). De plus, la situation alarmante des carences en micronutriments dans la région exacerbe cette situation et appelle à des stratégies efficaces pour lutter contre la malnutrition. Ainsi, le principal objectif de cette étude était d'identifier des hybrides de mil biofortifiés à haut rendement et d'établir une base scientifique efficace pour la sélection des hybrides en AO avec une adaptabilité dans la région. Les expériences ont été menées avec des répétitions dans différents endroits de AO. Le matériel expérimental consistait en une analyse L × T de 9 lignés et 12 testeurs, un diallèle complet de 6 restaurateurs et 30 F_1 et une évaluation de 68 hybrides simples et 42 hybrides topcross et des contrôles. Les effets *agc* ont révélé que, parmi les lignés, ICMB 177004, ICMB 177005 et ICMB 177007 étaient de bons combineurs généraux pour le nombre de jours à la date de 50% floraison ; ICMB 177002 et ICMB 177090 pour la longueur des épis ; ICMB 177111 pour la hauteur des plantes, la circonférence de l'épis et le rendement en grains. ICMB 177003 et ICMB 177001 étaient de bons combineurs généraux pour la teneur des grains en Fe et Zn, respectivement. Presque tous les testeurs étaient de bons combineurs généraux pour la hauteur des plantes. Les testeurs ICMR 08888, ICMR 1301 et ICMR IS 16007 étaient de bons combineurs généraux pour le nombre de jours à la date de 50% floraison ; ICMR 157003 et ICMR IS 16008 pour la longueur des épis ; ICMR 08666, ICMR 08777 et ICMR 157003 pour la circonférence des épis, ICMR 08666, ICMR 08777, ICMR 157003 et ICMR 157004 pour le rendement en grains. ICMR 08666 et ICMR 1301 pour la teneur de grains en Fe et Zn. Sur la base de *asc*, les hybrides ICMH 177016, ICMX 187851, ICMX 187892 et ICMX 187895 ont été identifiés pour le rendement en grains, la teneur des grains en Fe et Zn. Cinq hybrides, à savoir ICMX 187807, ICMX 187851, ICMX 187998, ICMX 1871029, ICMX 1871046 ont présenté une hétérosité positive à la fois par rapport au moyen des deux parents qu'au meilleur parent pour le rendement en grain, la teneur des grains en Fe et Zn. En ce qui concerne l'amélioration des restaurateurs, les croisements ICMX 1770192, ICMX 1770193, ICMX 1770194, ICMX 1770197, ICMX 1770204 et ICMX 1770208 ont montré des effets *acs* négatives importants pour le nombre de jours à la date 50% de floraison et des rendements en grains. Les effets *acs* positifs et significatifs pour la teneur des grains en Fe et Zn ont été exprimés par les croisements ICMX 1770197 et ICMX 1770204. Les restaureurs identifiés avec une bonne *acg* et des croisements avec une bonne *acs* séront utiles pour l'amélioration des lignées de restaureurs du mil afin de promouvoir la selection des hybrides en AO. Le rendement en grains est d'une importance économique pour lequel une variabilité considérable d'hétérosité a été enregistré dans un certain nombre de croisements comparer à CHAKTI et ICMV 167005 alors que, peu d'hybrides ont montré une hétérosité positive par rapport à CHAKTI pour la teneur de grains en Fe et Zn. En plus de leur avantage en termes de rendement, les hybrides topcross avaient montré certaines caractéristiques importantes comme la hauteur des plantes et la longueur des épis, aussi importantes que le rendement en grains pour un usage multiples. Alors que les hybrides simples se sont mieux présentés pour la biofortification. AMMI a identifiée, les hybrides ICMX 1871018 comme étant le plus stables pour le rendement en grains, ICMH IS 16187 pour la teneur des grains en Fe et ICMX 187778 pour la teneur des grains en Zn. L'indice de la stabilité a montré que les hybrides ICMX 187827, ICMX 187026 et ICMX 1871037 étaient les hybrides qui combinaient la stabilité à des rendements moyennes élevées, une teneur des grains élevée en Fe et Zn. Les hybrides ICMX 187830 et ICMX 1871042 combinaient une valeur moyenne élevée, une adaptabilité et une stabilité pour le rendement en grain, tandis que l'ICMX 187895 combinait des performances moyennes, une adaptabilité et une stabilité pour la teneur des grains en Fe et Zn. ICMX 187766 et ICMH 177016 combinaient une teneur élevée des grains en Zn, adaptabilité et stabilité. Les parents qui combinent bien pour le rendement, la teneur en Fe et Zn et d'autres traits seront utilés pour la production des hybrides biofortifiés, tandis que les hybrides stables et adaptés avec des rendement et des teneurs en Fe et Zn eleves pouraient etre vulgarises en AO.

Mots clés : Mil, Ligné × Testeur ; aptitudes à la combinaison, hétérosité, restaureur, diallèle analyses, hybride simple, hybride topcross, AMMI, adaptabilité, stabilité.

ABSTRACT

Pearl millet (*Pennisetum glaucum* L.), the world's sixth most important cereal crop is known as a climate smart crop due to its tolerance to drought, heat, soil salinity, low soil fertility, high nutritive and high capacity to buffer variable environmental conditions. Climate change and ecological production constraints is expected to increase the currently challenges facing by agriculture to ensure future food security for the growing population in West Africa (WA). Morever, the alarming status of micronutrient deficiency in the WA region exacerbates this situation and calls for effective strategies to combat malnutrition. Thereby, the main goal of this study was to identify the high yielding biofortified hybrids of pearl millet and establish an efficient scientific basis for hybrid breeding in WA with high adaptability across the region. The experiments were conducted in replicated trials in different locations of WA. The experimental material consisted of L × T analysis of 9 lines and 12 testers, a full diallel of 6 restorers and 30 F_1's and evaluation of 68 single cross hybrids and 42 top cross hybrids including the checks. *GCA* effects revealed that, among the lines, ICMB 177004, ICMB 177005 and ICMB 177007 were good general combiners for days to 50% flowering; ICMB 177002 and ICMB 177090 for panicle length; ICMB 177111 for plant height, panicle circumference and grain yield. ICMB 177003 and ICMB 177001 were good general combiners for grain Fe and Zn content, respectively. Almost all the testers were good general combiners for plant height. Testers, ICMR 08888, ICMR 1301 and ICMR IS 16007 were good general combiners for number of days to 50% flowing; ICMR 157003 and ICMR IS 16008 for panicle length; ICMR 08666, ICMR 08777 and ICMR 157003 for panicle circumference, ICMR 08666, ICMR 08777, ICMR 157003 and ICMR 157004 for grain yield. ICMR 08666 and ICMR 1301 for grain Fe and Zn content. On the basis of SCA, the hybrids namely ICMH 177016, ICMX 187851, ICMX 187892 and ICMX 187895 were identified as superior for grain yield, grain Fe and Zn content simultaneously across locations. Five hybrids namely, ICMX 187807, ICMX 187851, ICMX 187998, ICMX 1871029, ICMX 1871046 exhibited positive heterosis both over mid-parent and better-parent for grain yield, grain Fe and Zn content across locations. Regarding the restorer's improvement, the crosses ICMX 1770192, ICMX 1770193, ICMX 1770194, ICMX 1770197, ICMX 1770204 and ICMX 1770208 exhibited significant negative *sca* effects for days to 50% flowering with high grain yield. Positive and significant *sca* effects for grain Fe and Zn contents were expressed by crosses ICMX 1770197, and ICMX 1770204. Identified restorers with good GCA and crosses with good SCA, were useful in improving the restorer lines of pearl millet to promote the hybrid pearl millet breeding in WA. Grain yield is of economic importance for which considerable variable degree of standard

heterosis was registered in a number of crosses over CHAKTI and ICMV 167005 whereas, few hybrids showed positive heterosis over CHAKTI, check for grain Fe and Zn. Despite their yield advantage, top cross hybrids had shown some important characteristics like plant height and panicle length as important as grain yield for multiple purpose. While single cross hybrids were present better for biofortified hybrid of pearl millet. AMMI stability value (ASV) identified, the hybrids ICMX 1871018 to be the most stable for grain yield, ICMH IS 16187 for grain Fe content and ICMX 187778 for grain Zn. The stability index showed the hybrids ICMX 187827, ICMX 187026 and ICMX 1871037 as the hybrids that combined stability with high mean values for yield, high grain Fe and Zn content. The hybrids ICMX 187830 and ICMX 1871042 combined high mean value, adaptability and stability for grain yield whereas, ICMX 187895 combined high mean performance, adaptability and stability for grain Fe and Zn. ICMX 187766 and ICMH 177016 combined high grain Zn content with adaptability and stability. Parents which combine well for yield, Fe and Zn content and other traits will be used for the production of biofortified hybrids, while stable and adapted hybrids with high yields and Fe and Zn contents could be extended in WA.

Keywords: Pearl millet; Line × Tester; combining ability, heterosis, restorers, diallel analysis, single cross hybrid, top cross hybrid, AMMI, adaptability, stability.

CHAPTER I: INTRODUCTION AND GENERALITIES

1. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is the sixth most important cereal globally, next to maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and sorghum [*Sorghum bicolor* (L.) Moench] (FAOSTAT, 2017; Bidinger FR and Hash TC, 2004). It is the most important warm-season cereal crops worldwide primarily grown in Africa and India for food and fodder (Govindaraj *et al,* 2010).

Descended from a wild West African grass, it was domesticated more than 4,000 years ago, probably in what is now the heart of the Sahara Desert (Bidinger FR and Hash TC, 2004; Munson, 1975) when current drying period in this area necessitated a change from Mediterranean cereals to other species better adapted to changing rainfall patterns and increasing aridity (Brunken *et al*, 1977). Since, it was cultivated in the Sahelian and tropical countries, because of its developmental traits that provide specific adaptation to marginal and arid environments (D'Andrea AC and Casey J, 2002; D'Andrea *et al*, 2001; deWet *et al*, 1992). These include rapid germination of seeds, short length of key growing periods, high temperature tolerance, and the production of large seed numbers (Bidinger FR and Hash TC, 2004). Long ago it spread from its homeland to East Africa and then to India, 3,000 years ago (Brunken *et al,* 1977). Both places adopted it eagerly and it has become a much-favoured staple-food grain, feed grain and fodder crop.

Today, pearl millet is so important that it is sown on some ~22 million hectares in Africa and ~12 million hectares in Asia, as well as more than 3 million hectares in Latin America – where it serves as the best available mulch component (FAOSTAT 2017; Yadav *et al,* 2012; Andrews *et al,* 1993). Global production of pearl millet grain probably exceeds 30 million tons a year, (FAOSTAT, 2017). India is the largest producer, both in terms of area (9.1 million ha) and production (7.3 million t), with an average productivity of 998 kg/ha (Jagannah, 2017; Yadav OP and Rai KN, 2013) due to the use of hybrids in combination with improved crop management (Pucher *et al,* 2018). In Western and Central Africa (WCA), pearl millet is cultivated in 16 million ha with a production of 11.5 million tons and productivity of 500-600 kg/ha (Jagannah, 2017). Africa's major pearl-millet producing countries include Nigeria (5 M ha), Niger (7 M ha), Burkina Faso (1.5 M ha), Chad (3.0 M ha), Mali (1.5 M ha), and Senegal (1.0 M ha) in the west and central africa; and Sudan (2.0 M ha), Tanzania (0.2 M ha), Eritrea, Namibia and Uganda (0.1 M ha each) in the east (FAOSTAT, 2017; Andrews *et al*, 1993). At least 500 million people depend on pearl millet for their lives, which is a staple food crop throughout the year (Varshney *et al,* 2017; Rai *et al,* 2013; Gulia *et al,* 2007).

Pearl millet is a highly cross-pollinated cereal (more than 85% out-crossing) diploid (2n = 2x = 14), C_4 annual cereal crop with a very high photosynthetic efficiency and dry matter production capacity (Bachir *et al,* 2013; Yadav *et al,* 2012). Its floral biology is unique among the major crop species as its hermaphrodite flowers are protogynous (stigma emerging before anther emergence) with the fully emerged and unpollinated stigmas normally remaining receptive for 3–4 days before the pollen is released from the same panicle. Such a situation makes both crossing without emasculation and selfing convenient operations in breeding of pearl millet. Therefore, open-pollinated varieties (OPVs) and hybrids are the two broad cultivar options (Jukanti *et al,* 2016; Rai *et al,* 2013; Yadav *et al,* 2012).

Pearl millet is a highly nutritive crop among the several other nutri-cereals and research has shown good prospects of its nutritional value through genetic enhancement (Yadav *et al,* 2012). Besides being gluten-free, pearl millets have higher nutritional value than wheat, rice, maize, and sorghum, and are supplying 80 to 90% of the calories for many millions of poor people in semi-arid regions (Govindaraj *et al,* 2009). Its nutritional superiority comes from high levels of protein, vitamins, essential amino acids, antioxidants, and essential micronutrients, such as iron (Fe) and zinc (Zn) (Serba *et al,* 2017). Pearl millet grain is gluten-free millet and it is the only grain that retains its alkaline properties after being cooked so it is ideal for people with gluten allergies. Many traditional foods and beverages are made from pearl millet, including couscous, flatbreads, doughs, porridges, gruels, non-alcoholic beverages, and beer (Yadav *et al,* 2012).

Pearl millet is also a suitable feed ingredient in poultry diets. Its suitability for poultry diets ensures the bioavailability of micronutrients from its grain for monogastric animals and humans (Serba *et al,* 2017). Also, the stover is of great economic importance for livestock feed, building materials and fuel (Mason *et al,* 2015). By understanding the importance of this crop, various international institutions such as Bioversity International, Institute de Recherche pour le development (IRD) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have developed pearl millet improvement and conservation programs in most of the West African countries (Niger, Mali, Togo, Burkina Faso, Senegal, and Guinea) (Dagba *et al,* 2015).

The low productivity of pearl millet in West Africa is generally related to numerous biotic stresses (diseases, insect pests, and weeds) like downy mildew (caused by Scelerospora graminicola), head miner (*Heliocheilus albipunctella*) and the parasitic weed Striga hermonthica, which are also likely to get worse with changing climate patterns, as well as abiotic stress factors (heat, drought and low soil fertility) (Varshney *et al*, 2017; Haussmann *et al,* 2012). The development of resistant cultivars is apparently the most effective strategy to minimize losses by biotic and abiotic constraints, as the use of plant protection products and fertilizers are too costly for most pearl millet farmers and might have side effects on the environment, human health, and food safety (Pucher *et al*, 2018).

1.1. Context and justification of research

In West Africa, economy is highly dependent on agriculture, which is dominated by traditional, rain-fed, and small-scale production (Haussmann *et al,* 2012), and more vulnerable to climate change (Adger *et al,* 2003; Sarr, 2012). Pearl millet production in the region during the last two decades has increased by only 0.70 percent a year, the lowest record of productivity increase of any food crop in the region and far less than the population's growth rate (2.5%) (World Bank, 2017). Furthermore, even this small increase (0.70 %) has been mainly due to expanding the area cultivated rather than to boosting yields (Pucher *et al*, 2018). However, increasing the cultivated area in most of the developing countries of West Africa where 90% of the crop production growth is now limited. Elsewhere, it is estimated that the Sub Saharan African (included west Africa) population is expected to grow by 25% over the next 30 years to reach 3.36 billion in 2100 (Bongaarts J and Casterline J, 2013; Nelson *et al,* 2009) and pearl millet is expected to play an important role for achieving food security in West Africa. Such a population growth will put enormous pressure on food security, which is already insufficient in West Africa. The annual deficit of 9 million tons was recorded in West Africa and will be more than tripled by 2025 reaching unsustainable level (Lee *et al,* 2019; Cooper *et al,* 2008). By 2050, FAO (2006) projects that demand for cereals will increase by 70%, and will double in many low-income countries.

In West Africa, food security is mainly based on some cereals, pearl millet among them occupies a special place (Serba *et al,* 2017; Kanfany *et al,* 2018). It occupies 2/3 of the agricultural land (part of which in combination with other crops), and accounts for 73% of total cereal production (Saidou, 2009), 75% of total calories intake, 52% of *per* capita grain consumption, and one-third of protein intake (Haussmann *et al*, 2012). But the current pace of yield (≤0.60 t/ha) for pearl millet, is insufficient to meet future demand (Jagannah, 2017).

Besides, Lobell DB and Burke MB. (2010) predicted more than 15% decline by mid-century in the average production of pearl millet due to future changes in temperature and precipitation. According to Lobell *et al.* (2011), 1° C raise in temperature will reduce grain yield in about 65% of the current area in the region. The decline in yields whether, small or large, will impact negatively the population already vulnerable given the fact that over 80% of the population live in rural area and depend on rainfall agriculture for their livelihood. A climate sensitivity analysis of agriculture concluded that three African countries will virtually lose their entire rainfed agriculture by 2100 (Mendelsohn *et al*, 2000a, 2000b) and two of them are Sahelian countries: Tchad and Niger. Simulations worldwide show a relatively large decrease (20 to 50%) in the yields of cereal crops across Sahel, Niger and Senegal by 2050 (Sarr *et al,* 2007). Without effective intervention, projected increases in climate variability is expected to intensify the cycle of poverty, natural resource degradation, vulnerability and dependence on external assistance (Andreas, 2015; Lobell *et al,* 2013; Ruane *et al,* 2013; Waha *et al,* 2013; Jarvis *et al,* 2011).

More, in West Africa region, where significant portions of gross domestic product (GDP) (10% to 70%) are dedicated to agricultural production (Mertz *et al*, 2009; Mendelsohn *et al*, 2000C), approximately 85% of the population lives on less than US$1 per day (World Bank, 2017). Thus, they have lower capacity to adapt to climate change presenting a growing and variable challenge in the region. Thereby, the demand for high-yielding farmer-preferred varieties, the alarming prevalence of micronutrient deficiency calls for crops with enhanced nutritional value and adapted to specific agro-ecologies and a changing climate. Then, enhanced micronutrient density should be an additional goal to high yield and adaptation to climate change (Pucher *et al*, 2018). Thus, stable pearl millet biofortification of the grain for micronutrients, mainly iron and zinc could be one sustainable and cost-effective approach towards for reducing hidden hunger specially in West Africa (Kanatti *et al*, 2014; Rai *et al,* 2013; Bouis *et al,* 2011). Breeders and plant scientists from WA are under pressure to improve existing varieties and develop new ones that are high yielding, more nutritious, pest- and disease-resistant and climate-smart to help these vulnerable rural farmers who have no access to irrigation, affordable mineral fertilizer, pesticides or other purchased inputs to avoid large-scale human suffering (Lee *et al,* 2019). Hybrids is known to have high productivity, nutritional quality and more tolerant to biotic and abiotic stresses compare to OPVs. The hybrid of pearl millet production is one promising solution to be prospected in West Africa (Kapoor R and Singh P, 2017; Taye *et al,* 2016; Ouendeba *et al,* 1993; Andrews DJ and Kumar KA, 1992). Whatever, hybrid breeding in West Africa is primitive, still poorly documented and is yet to make a mark in West Africa (Pucher *et al,* 2018). So far, pearl millet hybrid breeding started some years ago at national levels, but it is still very limited and no hybrid seed is yet officially available on the seed market (Pucher *et al,* 2018).

1.2. State of knowledge

1.2.1. Pearl millet genetic diversity and improvement

Genetic diversity is the most important requirement for developing new cultivars with improved grain yield, quality, and tolerance to biotic and abiotic stresses (Govindaraj *et al,* 2019; Serba *et al,* 2017). Since pearl millet's domestication, selection processes have developed diverse cultivars adapted to different environments, suited to various production systems with different consumer preferences (Brunken, 1977). Several methods were used worldwide to assess and exploited genetic diversity for crop improvement and to simultaneously increase production and food security (Haussmann et al, 2004; Rai et al, 1997). Among them, germplasm evaluation and enhancement, genetic studies of traits of agronomic importance, development of cytoplasmic male sterility (CMS), and identification and utilization of dwarfing genes were important milestones (Serba *et al*, 2017; Bachir *et al*, 2013).

Globally, 66,682 accessions of pearl millet are conserved in 97 gene banks, in which, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has consolidated the largest collection in the world (Singh M and Upadhyaya HD, 2015). ICRISAT collection comprises of more than 20,800 cultivated pearl millet accessions and 750 wild relatives through 76 collection missions in 28 countries, most of these collections were made from West Africa, the center of diversity for pearl millet (Serba *et al,* 2017; Upadhyaya *et al,* 2016). These accessions showed substantial variability for quantitative traits as well as for qualitative traits, very crucial for crop improvement and can be utilized as parents in hybridization programs to produce superior hybrids/varieties (Dagba et al, 2015). Diverse germplasm that maintained broad genetic variability from natural genetic variation and breeding stocks created through crossing of diverse germplasm have been used by breeding programs to successfully develop high yielding and biotic as well as abiotic tolerant cultivars in wide range of climatic conditions (Serba *et al*, 2017). The wild relative, subsp. monodii, from West Africa with the prominent early-maturing, adapted to wide environment, grain nutritional quality and contributed desirable traits has been widely used for genetic improvement of pearl millet (Rai *et al*, 2015; Andrews DJ and Kumar KA, 1996).

Many tests based on morphological and physiological traits were conducted to assess the genetic diversity of millet in West Africa (Pucher *et al,* 2015; Dagba *et al,* 2015; Akanvou *et al*, 2012). Three gene pools were identified for crossing possibility, cross fertility, and gene transfer complexity from *Pennisetum* species to cultivated *Pennisetum glaucum.* The primary gene pool included all forms of cultivated, weedy, and wild diploids (2n = 2x = 14); the secondary pool consisted solely of tetraploid *P. purpureum* (Shum.) (2n = 4x = 28); and the tertiary pool included distantly related *Pennisetum* species of various ploidy levels (Dujardin M and Hanna WW, 1989).

1.2.2. Pearl millet production constraints and breeding targets in WA

Pearl millet is grown in semi-arid to arid zones where soils predominately have sandy textures, low organic matter and limited nutrient contents; rainfall is limited and erratic; air and soil temperatures are high; and the growing season length is short and varies greatly across years (Mason *et al,* 2015). Cropping in such harsh, rain-fed farming systems requires very high population buffering capacity, which can be achieved by varieties with high adaptation traits (Haussmann *et al,* 2012). Further, pearl millet is mostly cultivated on fields with very low soil fertility, extensive management practices and a low level of external inputs (Bekunda *et al,* 1997; Somda *et al,* 2002). The lack of financial resources, high prices, risk aversion and insufficient infrastructure inhibits many West Africa (WA) smallholder farmers from using fertilizers. Low phosphorus input especially will become an increasing constraint, since resources of phosphorus fertilizer are scarce and non-renewable.

Pearl millet breeding in West Africa has, therefore, the task of developing varieties that are highly adapted to low input conditions. Besides abiotic constraints, pearl millet has to cope with several biotic stresses (diseases, insect pests, and weeds) like downy mildew (caused by *Scelerospora graminicola*), head miner (*Heliocheilus albipunctella*) and the parasitic weed *Striga hermonthica*, which are also likely to get worse with changing climatic patterns. The development of resistant cultivars is apparently the most effective strategy to minimize losses by biotic constraints, as the use of plant protection products is too costly for the resource poor farmers and might have side effects on the environment, human health, and food safety.

West African farmers have very specific preferences in the characteristics of their pearl millet, making pearl millet breeding more complicated in the region (Puchet *et al,* 2018). Apart from grain yield, other traits like flowering time, panicle length, taste and high dual-purpose suitability (grain and fodder production) can have similar importance (Blümmel *et al,* 2003; Omanya *et al,* 2007). Thus, knowledge and consideration of region-specific farmer-preferred characteristics is crucial to develop improved varieties which will be adopted by the farmers. Such farmer preferences can be identified and achieved in participatory breeding programs (Christinck *et al,* 2005; Ceccarelli *et al,* 2009). As farmer preferences are highly region- and even social context-specific, there is no “one-size-fits-all” type of pearl millet that responds to the diversity of demands in the entire pearl millet growing area in West Africa. In addition to the plurality of pearl millet production constraints, there are only very few private seed companies in West Africa that produce and market seed which is hindering the development of pearl millet sector (Puchet *et al,* 2018).

1.2.3. Hybrid breeding in West Africa

Agriculture is the backbone of development in many countries, especially in the developing countries and innovation has played a major role in increasing production and productivity of many agricultural commodities. The concept of hybrid cultivars was one such innovation that has revolutionized the productivity and production of many staple food crops such as pearl millet, leading to substantial and sustained increase in production and productivity in the past five decades (Gowda *et al,* 2006).

The availability and knowledge of cytoplasmic nuclear male sterility lines (CMS) and their maintainers and restorers, made hybrid seed commercially viable (Burton, 1958; Athwal, 1965). Since the release of the first pearl millet grain hybrid (HB-1) in India in 1965 (Athwal, 1965a) and the first pearl millet grain hybrid, 'HGM 100' in the United States in 1991 (Gulia *et al,* 2007), providing the basis for enhanced hybrid research efforts (Matuschke I and Qaim M, 2008; Munasib *et al,* 2015). Actually, the prevalence of pearl-millet hybrids ranges from nearly 100% in the US, to approximately 50% in India (Havey, 2004). While, the prospect of hybrid breeding appeared bright and are yet to make a mark in West Africa, the origin and center of pearl millet diversification (Pucher *et al,* 2016; Haussmann *et al,* 2012; Ouendeba *et al,* 1993).

In West Africa, pearl millet breeding is mainly conducted by national breeding institutions with the major emphasis on developing improved populations and composites, and open-pollinated varieties (OPVs) and no hybrid is yet officially available in the seed market (Pucher *et al,* 2018). Several reasons that include: (i) seed production ease and economy; (ii) absence of an organized seed industry make development of OPVs continues to be the primary objective (Gowda *et al,* 2006). However, pearl millet hybrid research in West Africa should be in much better position than the rest of world due to the scientific knowledge and breeding materials generated from the region consider as the centre of diversification and origin of pearl millet.

The limited work done on hybrids in West Africa, however, has shown evident grain yield advantage of hybrids over OPVs in the absence of diseases in the Southern African Development Community (SADC) region (Monyo, 1998). Top cross and inter-population hybrids evaluated in the West and Central Africa region have shown up to 81% grain yield advantage and up to 23% stover yield advantage over OPVs (Ouendeba *et al,* 1993). Thus, the hybrid research emphasis in these regions has been on the top cross and inter-population hybrids, which being genetically more heterogeneous than single-cross hybrids, less vulnerable to downy mildew, ergot and smut. In contrast, India the largest producer worldwide that contributes nearly to half of world millet production, more than 70% of the production area is sown with freshly purchased single-cross hybrid seed (Yadav OP and Rai KN, 2013; Hash, 2002; Andrews DJ and Kumar KA, 1992). Such hybrids had substantial more than 40% grain yields advantage over popular open pollinated varieties (Mahadevappa and Ponnaiya, 1966). Dissemination of a large number and diverse range of improved breeding lines and hybrid parents developed at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and their extensive use both by the public and private sector research organizations have been central to this success. Also, establishment and growth of a vibrant pearl millet seed industry has played a critical role in diversifying the cultivar base with a diverse range of productive hybrids.

Initial characterization of West African pearl millet landraces for prospects of pearl millet hybrid breeding was conducted in WA (Pucher *et al*, 2016). Also, initial characterization of molecular diversity patterns of WCA pearl millet landraces was conducted in the BMZ Project "Mobilizing Regional Diversity for Creating New Potentials for Pearl millet farmers in West and Central Africa (2006–2009)". Meanwhile, inbred lines have been developed out of these populations, and need to be converted into maintainer/restorer versions for use in hybrid breeding (Gangashetty *et al,* umpublish).

1.2.4. Pearl millet hybrid parents research: Approaches and Achievements

Pearl millet is a protogynous species, where the stigma becomes receptive 2 to 3 d before the pollen is released from the same panicle and results in a higher proportion of cross pollination of over 85% (Desalegn *et al,* 2017). This protogynous flowering fulfils one of the essential biological requirements for hybrid development, able to enhance agronomic yield (*Reddy et al,* 2004; Rai *et al,* 1999). Nevertheless, hybrid parents research is needed to make significant contributions for efficient hybrid development strategies globally. Thus, the availability of stable cytoplasmic-nuclear male sterility (CMS) lines (A-lines), its maintainers (B lines) and restorer lines (R lines), have made the hybrid option commercially viable (Gowda et al, 2006).

New research areas have recently emerged in developing hybrid parents and continue to be the major research focus, in response to emerging challenges and opportunities. Conventional breeding approaches have provided a diverse range of parental lines for potential pearl millet hybrid breeding. As a result, continuing efforts were made to search for alternative CMS sources from A_1 CMS source during the 1960s and led to identification of A_2 and A_3 CMS sources from genetic stocks and their derivatives (Athwal, 1961; 1966), A_4 CMS and A_5 CMS sources from gene pools sources from *P. glaucum* ssp monodii accessions (Hanna, 1989; Rai, 1995). Based on the differential male fertility restoration patterns of hybrids, it has been established that the A_1, A_2, A_3, A_4 and A_5 were distinctly different CMS systems (Reddy *et al,* 2004). The availability of the more stable A_4 and A_5 CMS sources with high frequency of maintainers provides the mechanism for rapid conversion of any productive population into its male-sterile version.

In A-line breeding, development of productive B-lines with combinations of numerous agronomic and adaptation traits is the most difficult part of the program. Once this has been achieved, conversion of B-lines into A-lines is a rather straightforward exercise (Gowda *et al,* 2006). High grain yield potential of A-lines, both *per se* as well as in hybrids (ie., combining ability) is the most important consideration in seed parents breeding (A/B pairs). However, a few important considerations such as flowering time, plant height and panicle types do merit rational judgment. It is highly preferred that the difference between the flowering time of an A-line and B-line be as less as possible for synchronous flowering and breeding efficiency increase (Gowda *et al,* 2006). Also, the height of an A-line should be no less than that of a B-line and vice versa.

Restorer lines (R-line) must produce profuse pollen that should remain viable at air temperatures as high as 42−44°C. Also, pollen parents must produce highly fertile hybrids, which confers some degree of protection from ergot and smut infection (Gowda *et al,* 2006). Besides being able to produce high-yielding hybrids, the restorers should also be highly productive, which is important from the viewpoint of seed production economy. It is desirable to breed pollinators of 150−180 cm height, but no less tall than the A-line, with panicle, maturity and tillering attributes that will be preferred by farmers in the hybrids. In restorers' parent's improvement programme and genetic studies, inbred lines that restore male fertility of two CMS systems (dual-restorers) and those that restore male fertility of several CMS systems (multiple-restorers) are useful.

In West Africa, an exploratory study on the feasibility of using currently available seed-parents from India and Nigeria with A_1 cytoplasm for pearl millet hybrids in WCA indicated that these parents had sterility breakdown and were too early maturing, thus requiring new, adapted seed parents for viable hybrids (Gangashetty *et al,* umpublish). A small but genetically diverse range of new pearl millet seed parents (A-/B-pairs), and restorer lines (R-lines) for two superior cytoplasmic male sterility systems (A_4 and A_5) have recently been introduced from India along with several A/B-pairs previously developed in WA. Further, crosses were made at ICRISAT, Niamey, Niger to initiate conventional backcrossing of fertility restoration alleles from the introduced restorers into locally-adapted population backgrounds.

1.2.5. Cytoplasmic male sterility for hybrid seed production

Cytoplasmic-nuclear male sterility is a physiological abnormality, resulting from a disharmonious interaction between the cytoplasmic factors (now widely identified as mitochondrial genetic factors) and nuclear genetic factors, leading to the production of degenerated or non-viable pollen grains or non-dehiscent anthers with or without functional pollen grains (Reddy *et al,* 2004). Or simply the inability of plants to produce functional pollen grains. It is a potential system for economical hybrid seed production. On one hand, cytoplasmic male sterility (CMS) is a maternally-inherited trait characterized by the absence of functional pollen (Burton, 1958). Ideally, a commercial male sterile line should neither shed pollen nor should it set seed when selfed, regardless of the location and the season. The occurrence of CMS in some of the crop plants is best utilized as an important genetic tool in hybrid breeding (Chandra-Shekara *et al,* 2006). Nevertheless, evaluation of different cytoplasmic sources with various pollinators is important in breeding programmes (Yadav, 1994).

In pearl millet, CMS was discovered in the United States in 1956 in F_2 population derived from a cross Tift 556 × Tift 23 (Burton, 1958; Menon, 1959) and the first released male-sterile derived was termed A_1 or milo cytoplasm, provided a viable and economical way of producing hybrids and exploiting hybrid vigor in pearl millet breeding programs (Chotaliya *et al,* 2009).

Most, if not all, of the world's hybrid pearl millet is produced using the A_1 cytoplasm (Smith RL and Chowdhury MKU, 1989). However, Tift A_1 CMS used to produce commercial hybrids presented potential sensibility to diseases especially downy mildew. Therefore, genetic diversification in A_1 cytoplasm as well as diversification of CMS sources is required to reduce the risk of disease epidemics associated with genetic and cytoplasmic uniformity .Several other CMS sources, classifying in five mean groups A_1 (Tift A_1), A_2 (Tift A_2), A_3 (L67 A_3), A_4 (monodii) and A_5 (LSGP) were identified based on the field studies of male fertility restoration in hybrids (Akenova, 1982; Appadurai *et al*, 1982; Rai KN and Hash CT, 1990; Marchais L and Pernes J, 1985; Aken Ova, 1981, 1985; Hanna, 1989). Among them, three sources of CMS systems (A1, A_4 and A_5) have been identified for commercial purpose in pearl millet which produce A-lines with no pollen shedders (Yadav et al, 1993). Thus, the A1 have more restorers' lines and ideal for hybrids production, whereas, the A_4 and A_5 CMS systems with more stable male sterility and higher maintainer frequency have provided great opportunities for CMS genetic diversity of A-lines in pearl millet (Rai *et al,* 2009). These include stability of male sterility, maintainer gene frequency in germplasm, character association, and male fertility restoration behaviour. However, the very low frequency (< 10 %) of restorers of the A_4 and A_5 CMS system in pearl millet poses problems in its utilization for grain hybrid program (Gowda *et al,* 2006).

1.2.6. Combining ability and heterosis in pearl millet

Proper choice of parents is very useful for successful development of hybrid program (Baker, 1978; Falconer, 1989; Griffings, 1956). Therefore, there is a need to make a proper choice of parents that will provide potential progenies. Combining ability describes the breeding value of parental lines to be selected in the breeding programs for production of superior hybrids is one of the powerful tools (Govindaraj *et al,* 2013). It refers to the capacity or ability of a genotype to transmit superior performance to its crosses.

The concept of combining ability was first proposed by Sprague GF and Tatum LA. (1942) in maize and has been used successfully in several studies. It is of two type: general combining ability (GCA) and specific combining ability (SCA). The general combination ability refers to additive gene action and is used to determine the performance of parents in general terms, while specific combining ability effect is determined by dominant gene action and is used to indicate the hybrid performance in specific crosses.

Diallel (Griffing, 1956) and line × tester (Kempthorne, 1956) matting designs provide reliable information about the general and specific combining ability of parents and their cross combinations. The knowledge of combining ability and gene action would help breeders to effectively identify potential parents, breeding strategies and to select promising genotypes from the segregating populations to improve productivity.

In pearl millet, highly outcrossing species, the development of male sterility for suppressing self-pollination made exploitation of hybrid vigor a potential to enhance agronomic yield (Serba et al, 2017). Thus, the introduction of CMS inbred line Tift $23A_1$ in India in 1962 (Burton, 1969) replaced the hand pollination and allow hybrid vigor exploitation throughout heterosis breeding. For example, the first hybrid HB-1 yielded, on average, 88% more than the best local cultivars (Athwal, 1965). Since the heterosis or hybrid vigour proposed by Shull. (1914) referring to the increase or decrease vigour growth, fitness or yield of a hybrid over the parental values, resulting from the crossing of genetically unlike organisms has been widely used (Mather K and Jinks JL, 1971; Fonseca S and Patterson FL, 1968). Generally, positive heterosis is considered as desirable. But in some cases, negative heterosis is also desirable. For example, negative heterosis, for maturity duration and toxic substances is desirable in many cases because it shows superiority over parents or checks.

Heterosis is estimated in three orders: over mid parent heterosis, over better parent heterosis and over commercial sheck. However, commercial exploitation of hybrid vigour came into light only when Stephens JK and Holland RF. (1954) reported for the first time, the use of cytoplasmic genetic male sterility for developing hybrids.

For yield, heterosis of 40% and above over the better parent is considered significant from practical point of view in most of the crop plants. It is confined only to the F_1 generation of a cross. It declines and disappears in F_2 and subsequent generations of a cross as a consequence of segregation and recombination. However, the manifestation of heterosis is more pronounced in the area of adaptation of a hybrid and once identified, it can be easily reproduced under the same set of environmental conditions.

Studies on population hybrids of African landraces reported the prevalence of a high level of heterosis that can potentially contribute to enhancing productivity in the Sahelian and Sudanian environments of West Africa (Ouendeba *et al,* 1993; Pucher *et al,* 2016).

1.2.7. Micronutrient deficiency and biofortification in pearl millet

Micronutrient malnutrition resulting from dietary deficiency of one or more micronutrients affect more than 2 billion people worldwide (Kanatti *et al,* 2014; Muthayya *et al,* 2013). It has been recognized as a serious human health problem worldwide (Black *et al,* 2013; Bouis *et al,* 2011; UN SCN, 2004).

Among the top 20 risk factors contributing to global burden of disease, iron (Fe) and zinc (Zn) deficiencies rank 9th and 11th, respectively (WHO, 2002). In low and middle-income countries where the population is dependent on one staple crop, the most widespread are dietary deficiencies in iron (Fe), zinc (Zn) and vitamin A (ß-carotene) (Kanatti *et al,* 2014). Because of low diversity source of micronutrient in their dietary consumption (Muthayya *et al,* 2013).

These nutritional deficiency problems have enormous socioeconomic impacts at the individual, community and national levels (Darnton-Hill *et al,* 2005). They have an immense impact on the health of the population, learning ability and productivity. Young children and pregnant women are most vulnerable to micronutrient deficiencies because of their rapid growth and development stage (Black *et al,* 2013).

Various approaches have been developed and applied to prevent micronutrient deficiencies such as pharmaceutical supplementation, industrial food fortification, and agricultural approaches of dietary diversification and biofortification (Kanatti *et al,* 2014). Biofortification, a new approach that relies on conventional plant breeding and modern biotechnology to increase the micronutrient density of staple crops holds great promise for improving the nutritional status and health of poor people with limited access to diverse diets, supplements, or commercially fortified foods (Bouis, 2003). It has been identified as a sustainable and cost-effective approach for combating major global health problems, such as iron and zinc deficiency, acceptable by consumers as their adoption does not call for change in dietary habits (Kanatti *et al,* 2014; Huey *et al,* 2018). Thereby, during the last decade, significant progress has been made in the international crop breeding community to boost the nutrient concentration of staple crops through a biofortification approach (Pfeiffer WH and McClafferty B, 2007). Initial efforts have focused on the development of Zn-dense wheat (*Triticum aestivum* L.), rice and cowpea (*Vigna unguiculata* L.) (Andersson *et al,* 2017), and Fe dense pearl millet and common bean (*Phaseolus vulgaris* L.) (Saltzman *et al,* 2017). Then, since HarvestPlus Phase I (Discovery, 2003–2008), ICRISAT initial screening of germplasm accessions in pearl millet and found ranges of 30–76 ppm iron (and 25–65 ppm zinc); high-iron genotypes were selected to initiate crosses (Velu *et al,* 2007). Biofortification breeding is usually focused on the most limited nutrients in human diets such as Fe and Zn, without considering other essential minerals. But since iron deficiency is a more widespread and serious problem than zinc deficiency, and much larger variability has been observed for iron than for zinc content, research at ICRISAT has focused on genetic improvement of iron content, with zinc being improved as an associated trait, considering that both traits are highly significantly and positively correlated (Rai *et al,* 2013). Therefore, in breeding process, it is crucial to know the interrelationship among target mineral grain densities (Govindaraj *et al,* 2013). Development of pearl millet hybridswith high grain yield associated with grain Fe and Zn content could contribute to the reduction of Fe and Zn deficiencies in millet-dependent populations in WCA (Hama *et al,* 2012; Pucher *et al,* 2014). Studies in India have shown that total iron and zinc absorbed from biofortified pearl millet variety with high levels of these micronutrients were higher than those from the non-biofortified variety, implying the significant contribution that biofortification can make in addressing their deficiencies in the population consuming this nutritious cereal (Huey *et al,* 2018). Thus, biofortification of pearl millet is the most cost-effective, sustainable, consumer acceptable for the 90 million people heavily dependent of pearl millet-based diets (Rai *et al,* 2013). Therefore, nutrient density traits must be transferred to high-yielding cultivars. ICRISAT, supported by the HarvestPlus Challenge Program of the CGIAR and in partnerships with the public and private sector research organizations, has initiated a major effort to develop pearl millet cultivars with high levels of these micronutrients. This initiative, focus, first, on exploring the available genetic diversity for micronutrients such as Fe, Zn, and ß-carotene (provitamin A) to identify parental genotypes that can be used in crosses, genetic studies, molecular marker development, and hybrid parent-building (Pucher et al, 2014; Govindaraj et al, 2009). To have a high adoption and maximum impact, high-yielding genotypes with excellent, farmer-preferred grain quality are needed (Pfeiffer WH and McClafferty B, 2007; Graham et al, 2001). Then, several reports indicate the existence of large variability for grain Fe and Zn concentrations in pearl millet. For example, a recent study by Pucher et al. (2014) of 72 pearl millet accessions from West and Central Africa (WCA) assessed in Niger showed moderate ranges in mineral density (24.2 to 48.7 mg kg^{-1} for Fe and 19.8 to 43.4 mg kg^{-1} for Zn). A study focusing on the grain mineral density of 225 Sudanese pearl millet accessions evaluated in Sudan also found wide variation for Fe and Zn ranging from 19.7 to 86.4 mg kg^{-1} for Fe and 13.5 to 82.4 mg kg^{-1} for Zn (Bashir et al, 2014). Recently (2018), ICRISAT, Niamey, Niger has released Africa's first biofortified pearl millet variety (CHAKTI) with 65 mg kg^{-1} for Fe and 58 mg kg^{-1} for Zn (Gangashetty et al, umpubish paper).

For biofortification to be successful, three important things must be considered; the possibility of breeding to increase the micronutrient density in staple food to a level that will have a significant impact on nutritional status, the bioavailability and absorption of the extra nutrients bred when consumed under controlled conditions and the acceptance and adoption of the biofortified varieties by farmers and consumers (Howarth *et al*, 2011).

1.2.8. Pearl millet–a food security crop

Pearl millet is one of the most important staple food crops of arid and semi-arid tropics of Africa and Asia (Sanjana, 2017; FAO, 2014). It is a major food and feed crop of subsistence poor farmers in hot and dry environments throughout the semi-arid tropics (Taylor *et al*, 2016; Singh *et al*, 1997), where cropping of other cereals is not productive due to the very harsh environment (Dagba *et al*, 2015). It is a staple food crop for about 90 million people living in the semi-arid tropical regions of Africa and Asia (Gulia *et al*, 2007). Besides being gluten-free, pearl millet is rich in major and minor nutrients required for well-being, have higher nutritional value than other cereals, and are supplying 80 to 90% of the calories for millions of poor people living in the semi-arid regions (Govindaraj *et al*, 2009).

The grain is used mainly as a whole, cracked, or ground flour, a dough, or a grain like rice and is actually a superior foodstuff, containing at least 9 percent protein and a good balance of amino acids. It has more oil than maize and is a "high-energy" cereal. Pearl millet grain are made into unfermented breads (roti), fermented foods (kisra and gallettes), thin and thick porridges (toh), steam-cooked dishes (couscous); nonalcoholic beverages, and snacks. In future, the importance of pearl millet will grow and may be used in many more types of foods. Nutrition studies show that pearl millet has the potential to fight Fe deficiency, a widespread micronutrient deficiency and a major cause of anaemia, affecting the health and development of a third of the global population (UN SCN, 2004).

Several other features that make pearl millet an ideal crop for food security are it is basic and applied research, short life cycle, high number of seeds per panicle, good seed transplanting success and a low seed rate specially in the context of climate change and growing population (Yadav *et al,* 2012).

1.2.9. Climate change, state of knowledge and impacts on WA agriculture

Climate change is a major environmental challenge to the world today, with significant threats to ecosystems, food security, water resources and economic stability overall. It is certainly the most discussed issue of the first decade of the 21st century, being discussed worldwide and defined by many institutions (Cooper *et al,* 2008). In its current global context, sustainable crop production is one of the major challenges (Ghatak *et al,* 2017). Moreover, the IPCC (2007) report, that climate will continue to change due to the increase of global temperature (1.1–6.4◦C), drought and some extremes events thus raises many questions related to food security.

All regions are challenged by climate change but Africa is considered particularly vulnerable to climate change, due to a combination of naturally high levels of climate variability, high reliance on climate sensitive activities, limited economic and institutional capacity to cope with, and adapt to, climate variability and change (CCAFS, 2015; IPCC, 2007). Furthermore, under its current climate of Africa is already facing recurrent food crises and water scarcity which are exacerbated by rapid population growth. Climate change will thus, act as an additional stress in the future of African economies and livelihood (Richard *et al,* 2012).

Among Africa region, West Africa is considered to be highly vulnerable to the impacts of climate change due to its extreme aridity, limited adaptive capacity and dependence on rainfall agriculture, highly sensitive to climate change (Lobell D and Burke M, 2010; Maria, 2010). Moreover, the environment of West Africa within which agricultural crops and agronomic practices are developed is rapidly changing due to climate change (Teixeira *et al*, 2013). Adverse changes in climate are likely to directly impact agricultural systems, thereby threatening food security and economic growth (Roudier *et al*, 2011).

In WA, observed temperatures have been increasing faster than global warming. The increase varied between 0.2 and 0.8◦ C since the end of the 1970s (Sarr, 2012). Thus, temperature controls the rate of plant metabolic processes that ultimately influence the productivities of crops (Hay RKM and Walker AJ, 1989). High average "seasonal" temperatures can increase the risk of drought, limit photosynthesis rates and reduce light interception by accelerating phenological development (Tubiello *et al*, 2007). Heat stress damage is particularly severe when high temperatures occur concomitantly with critical crop development stages, particularly the reproductive period. Regarding this, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has acknowledged heat stress as an important threat to global agriculture (IPCC, 2007). Currently, there is a lack of understanding on the spatial distribution and intensity of crop damage caused by heat stress. Spatially, heat stress damage is expected to vary with climate, land suitability for production and the sensitivity of cultivated crops. Drought, in most cases, causes crop failure (Benson C and Clay E, 1998). The climate of WA is also influenced by anthropogenic impact from land use changes, which affect vegetation cover, and soil moisture (Douville, 2002). So, climate change will intensify the already adverse conditions of crop production in West Africa considering the socio-economic, political contexts of climate change and the dependency on rain-fed agriculture (Chinwe, 2010). Moreover, climate change and associated problems of rising temperatures, water shortages, recurrent droughts, and soil salinity are increasingly becoming more serious problems to agricultural production in West Africa (Chinwe, 2010). Warmer air temperatures have already affected the length of the growing season over large parts of West Africa. Flowering and harvest dates for cereal crops are now happening in abnormal days in the season and these changes are expected to continue in many countries (Roudier *et al*, 2011). Changes in temperatures and growing seasons might also affect the proliferation and the spreading of some species, such as insects, invasive weeds, or diseases, all of which might in turn affect crop yields (Cooper *et al*, 2008).

In many countries of West Africa, where agricultural output depends on rainfall the production could decrease by 50 % by 2020 (IPCC, 2007). In the particular case of arid and semi-arid areas, consider as pearl millet production area, that are distinguished from others by a higher degree of vulnerability; either due to greater climate uncertainty or to an excessive imbalance between population and resources distribution (soil erosion, overgrazing)

(Cambrezy L and Janin P, 2003). Therefore, climate phenomena reveal, and amplify the underlying problems related to the vulnerability of societies (Carrega *et al*, 2004).

Modern agriculture has progressed by weakening the downside risks of climate factors through improved agronomic practices, adoption of precision input management the use of biological pesticides and fertilizers, the manipulation of genetic resources and plant breeding for adapting crop to farmers practices (Sapkota *et al*, 2017).

1.2.10. Crops adaptation to climate change

Future climate change is expected to intensify the already observed lowest record of crop productivity increase in West Africa if no remedial actions are taken to reduce emissions and transforming current energy systems. Even without climate change, there are serious concerns that make crop production challenging in semi-arid region, where pearl millet is a staple crop because of water supply variability, soil degradation, and recurring drought events (Mendelsohn et al, 2000). Further, development efforts have been particularly difficult to sustain the crop production and food security (Mendelsohn et al, 2000). Hence, the agricultural production needs to adapt to a changing climate without contributing to greenhouse gas emissions.

Several adaptation options are already used at the local scale by West Africa farmers to limit future yield losses. They are generally farm production practices (e.g. water management, selection of crop landraces, crops rotation and association, agroforestry, fertilization) but also income/asset management (e.g. diversification of activities, migrations) (Garnett *et al*, 2013; Butt *et al*, 2005). Many of the adaptation practices like mixed cropping, green manures that fix nitrogen, agro-forestry and improved range land management sequester carbon, thereby reducing greenhouse concentrations in the atmosphere (IPCC, 2007). Other measures like rain water harvesting and soil conservation measures reduce soil erosion and the silting of rivers. The contributions of agro-forestry to resilience, carbon sequestration, nitrogen fixation and a source of income are similar to those of crop management practices. In line with linking adaptations to poverty reduction, farmer-preferred cultivars that enhanced nutritional value and adapted to changing climate will be found to be a sustainable adaptation strategy that could attract the breeders, farmers and Climate experts worldwide.

1.2.11. Pearl millet – a climate smart crop

Pearl millet is a climate resilient crop due to its ability to adapt and cultivate despite the global warming phenomenon, release less greenhouse gases, less resource-intensive, and rich in major and minor nutrients required for well-being (Varshney *et al*, 2017; Gupta et al, 2015). It has high photosynthetic efficiency, dry-matter production, well adapted to drought prone areas, low soil fertility and high temperature (Jagannah, 2017; Singh *et al*, 1997). It is hardy cereal crop with short growth periods (60–100 days) in semi-arid to arid zones where soils predominately have sandy textures, low organic matter and nutrient levels; rainfall is limited and erratic (annual precipitation as low as 300 mm), air and soil temperatures are high; and the growing season length varies greatly across years (Mason *et al*, 2015).

Pearl millet is usually grown under the most adverse agro-climatic condition where other crops fail to produce economic yields, because of its capacity to fixe carbon even under high temperatures and low nitrogen conditions and its low transpiration rate (Manning *et al,* 2011). In spite of this, pearl millet has remarkable ability to respond to favourable environments because of its short developmental stages and capacity for high growth rate (Yadav *et al,* 2012). Thus, pearl millet has the ability to cope with climate variability due to its high buffering capacity, specific adaptation traits such as resistances to drought, high temperature and flooding and its genetic variability (Serba *et al*, 2017).

Furthermore, pearl millet has great potential as an excellent genomic resource for isolation of candidate genes for tolerance to drought and heat stresses to buffer variable environmental conditions (Haussmann *et al*, 2012). Significantly, only a few loci changes appear to be, and cultivated pearl millet retains many of the valuable adaptive features of its wild progenitor, which are responsible for its unique adaptation to environments characterized by variable moisture patterns, high temperatures, and short growing seasons. (Poncet *et al,* 2002). Besides to its adaptive features, it is an excellent research organism, genetically manipulated because of many desirable characteristics and natural genetic abundant diversity (Mason *et al,* 2015). These include the production of 1000–3000 seeds per panicle, the ability to exploit protogyny without emasculation, the ability to exploit both population and pure-line plant breeding techniques, and the existence of significant heterosis and multiple cytoplasmic-genetic male-sterility systems (Jat *et al*, 2012). Its molecular genetic traits make it uniquely suitable among the major cereals for the application of molecular techniques of crop improvement. These include its diploid nature (2n = 14) and large chromosomes, its moderate haploid DNA content and relatively low recombination rates (resulting in a short genetic map), its high degree of polymorphism at both phenotypic and molecular levels, plus the ease with which both self- and cross-pollinated progenies can be generated (Bidinger FR and Hash TC, 2004).

Pearl millet has much to offer to the improvement of other cereals. It has fewer insect pests and suffers less from diseases than sorghum, maize, or other grains. Pearl millet can be grown as a sole crop or in intercropping systems with cowpea (*Vigna unguiculata* (L.) Walp), groundnut (*Arachis hypogaea* L.), grain sorghum, or maize (Yadav OP and Rai KN, 2013; Reddy *et al,* 1992), and often in agroforestry systems (Reij CP and Smaling EMA, 2008) and adapt to climate change (Jat *et al,* 2012). There remarkable adaptation attributes and the ability to respond favourable to external inputs, place pearl millet in a unique advantageous position to face emerging challenges, especially in view of climate change (Yadav et al, 2012). Moreover, researchers have shown that millet perform well in high heat and low water conditions, release less greenhouse gases, which could be beneficial in reducing the contributions of the agri-food sector to global warming, in the context of climate change — this is the crop for the future. Nevertheless, for pearl millet to fully become an alternative crop, its remarkable attributes rank, should frequently be stable over environments and years.

1.2.12. Genotype × Environment interaction for stability and adaptability in pearl millet

Environmental changes affect quantitative as well as qualitative traits of crop due to significant genotype × environment interactions (G×E) (Scheelbeeka *et al,* 2018Tuberosa, 2012). The ability of crop varieties to perform well over a wide range of environmental conditions has long been appreciated by plant breeders (Finlay KW and Wilkins GN, 1963). The most reliable way to evaluate a cultivar is to grow it in multiple environments or in the same environment for several years or both (in multiple environments for several years) The selection of suitable breeding and testing locations is crucial to the success of a plant breeding program for more stable performance. Besides, an ideal test location should not only be able to discriminate the genetic differences among genotypes, but also target environments for which selected genotypes are best adapted (Luo *et al,* 2015). In the cereal belts of West Africa this has proved to be of particular importance, because edaphic variation between localities and the seasonal variation are very great. Even in a uniform edaphic environment a considerable degree of general adaptability will be important, because of the marked fluctuation of climatic conditions from season to season.

Unpredictably variable rainfall across different sites and years may cause genotype by environment (G×E) interactions that need to be considered by the plant breeders in order to identify the best genotypes that produce stable performance over years and, therefore contribute to food security of smallholder farmers (Pucher *et al,* 2018). Regarding the responsiveness of crop to their environment variation, one of the most challenging aspects of adapting crops to climate change will be to maintain their better performance over wide range of environment (Gregory *et al,* 2009). Hence it is important to examine G × E interaction and assess its magnitude in different environments and ecological regions. Due to the fact that the existence of genotype-environment interaction (GEI) complicates the identification of superior genotypes for a range of environments and calls for the evaluation of genotypes in many environments to determine their true genetic potential (Yaghotipour A and Farshadfar E, 2007). The importance of G × E interactions in breeding programs have been demonstrated in almost all major crops, including pearl millet genotypes (Kanfany *et al,* 2018, Sumathi *et al,* 2017; Bachir *et al,* 2014). Some cultivars are well adapted to specific ecological regions; that is, they show similarities in development potential and constraints under specific environments, or where the same group of cultivars forms the best combination year after year (Yan *et al,* 2010). Consequently, multi-environment trials (METs) are widely used by plant breeders to evaluate the relative performance of genotypes in different types of environment (Delacy *et al,* 1996).

Various statistical methods (parametric and non-parametric) have been proposed to study Genotype × environment interactions (Mohammadi *et al,* 2010; Hussein *et al,* 2000; Crossa, 1990; Becker HC and Leon J, 1988;). One of the multivariate techniques is the AMMI (Additive Main Effects and Multiplicative Interaction) model approach as a measure of stability and adaptability, wildly used (Luo *et al,* 2015; Yahaya *et al,* 2006). The AMMI model combines the analysis of variance for the genotype and environment main effects with principal components analysis of the G ×E interaction (Zobel *et al,* 1988; Gauch HG and Zobel RW, 1996).

Different concepts and definitions of stability have been described over the years. Lin *et al.* (1986) identified three concepts of stability (Type 1, 2, 3), later Lin CS and Binns MR. (1988) proposed a fourth type (Type 4). However, the quantitative measure of stability will not be provided by by AMMI analysis, so Purchase *et al.* (2000) developed the AMMI stability value (ASV) based on the AMMI model's IPCA1 and IPCA2 (interaction principal components axes 1 and 2, respectively) scores to quantify and classify each genotype according to its *per se* potential. Thereby, smaller ASV scores indicate a more stable genotype across environments (Adjebeng-Danquah *et al,* 2017; Sumathi *et al,* 2017). In addition, Farshadfar *et al*. (2011) and Tumuhimbise *et al.* (2014) used stability index (SI) to identified genotypes which combined high performance with stability. SI is the the sum of the ranking based on the traits study and ranking based on the AMMI stability value (Adjebeng-Danquah *et al,* 2017).

In general, stability parameters are employed to describe the adaptation behaviour of genotypes in diverse environmental conditions (Finlay KW and Wilkinson GN, 1963; Eberhart SA and Russell WA, 1966). Two major concepts of stability have been distinguished in relation to G×E interaction; 1) the stable genotype maintains constant performance across different environments ("static" stability concept); 2) the response of a stable genotype to environments is parallel to the mean response of all genotypes in the trial ("dynamic" stability concept) (Becker HC and Léon J, 1988). Thus, two types of G × E, namely quantitative and qualitative have been identified. Quantitative interaction is the change in the magnitude of differences among genotypes in different test environments without any rank changes. Change in rank orders, or crossover interaction, is a qualitative type of interaction and is the most important in plant breeding because it prevents prediction of genotype performance on different locations, during different years or both. (Annicchiarico, 2002; Pswarayi *et al,* 2008).

1.3. Research hypothesis

Pearl millet hybrid breeding in West Africa has the potential to increase pearl millet productivity and nutritional value under climate change by utilizing the enormous hybrid parents' diversity and biofortification breeding programs. Thus, the present research investigation has to test four hypotheses corresponding to the four specific objectives.

i. Combining ability, is one of the powerful tools to identified parents and good hybrid combination.
ii. The restorers from West Africa are component of genetic diversity that provide raw material for breeding new improved restorers for strengthening hybrid of pearl millet breeding in the context of climate change.
iii. Commercial heterosis over released improved OPVs is the useful approach to assess the superiorities of hybrid.
iv. AMMI is a useful model to get information on stability and adaptability in the wide range of environments.

1.4. OBJECTIVES

1.4.1. Overall objective

The overall goal of the present research investigation was to enhance pearl millet productivity and nutritional quality under climate change in West Africa through cultivation of high yielding nutritious hybrids.

1.4.2. Specific objectives

In particular, the objectives of this research study were:

i. Assessment of Combining Ability among Hybrids of Pearl Millet Parents for Efficient Pearl Millet Hybrid Breeding in West Africa.
ii. Genetic Improvement of Restorer Lines for Strengthening Pearl Millet Hybrid Breeding in West Africa.
iii. Estimation of Commercial Heterosis in Single and Top Cross Hybrids of Pearl Millet.
iv. Multilocation Testing of Single and Top Cross Hybrids of Pearl Millet for Grain Yield, Grain Fe and Zn stability and adaptability in West Africa.

Achieving these objectives is expected to open a door for high yielding adapted biofortified hybrids that will boost the economy and help the resource poor farmers in West Africa.

CHAPTER II: MATERIALS AND METHODS

2.1. Experimental area

The study was carried out in Sadore located in Niger, Gampela in Burkina Faso and Cinzana in Mali corresponding to three Sahelian countries of West Africa. In these countries, pearl millet is first or second most important crop in terms of area sown, production and consumption. The geographic coordinates, type of soil, weather data during the crop season for each locality are given in Table 1.

Table 1. Geographic coordinates and some climatic data of the experimental sites (Sadore, Gampela and Cinzana)

Location	Geographic coordinates			Soil	Weather data during the crop season		
	Latitude	Longitude	Altitude	structure of soil	Rain fall (mm)	Minimum temperature (°C)	Maximum temperature (°C)
Sadore (Niger)	13.23	2.28	235	Sandy	591	24.20	43.13
Gampela (Burkina Faso)	12.42	1.35	275	Sandy Loam	751	23.40	35.50
Cinzana (Mali)	13.25	5.97	282	Sandy Loam	759	23.30	36.30

Source : https://en.tutiempo.net/climate/africa.html

2.2. Experimental material

The experimental material used for all the trials was obtained from ICRISAT, Sahelian centre, Niamey, Niger. The test materials were selected based on differences on variability for agromomic traits such as tillering, plant height, panicle size, maturity, 1000-grain mass and grain Fe and Zn content.

Objective 1: The material was comprised of nine lines *viz.*, ICMB 177001, ICMB 177002, ICMB 177004, ICMB 177090, ICMB 177111 (these are A_1 CMS); ICMB 177003, ICMB 177005, ICMB 177006 and ICMB 177007 (these are A_4 CMS) and twelve testers *viz.*, ICMR 1301, ICMR 08666, ICMR 08777, ICMR 08888, ICMR 09666, ICMR 157003, ICMR 157004, ICMR 167006, ICMR 167007, ICMR 167008, ICMR 167011 and Exbornu (A_1 CMS); mating in L× T design to obtain 108 crosses (Annexure 1). These lines and testers were selected based on their nicking with the female lines. The 108 crosses and their 21 (9 lines and 12 testers) parents were used to determine the combining ability studies.

Objective 2: In order to strengthening pearl millet hybrid breeding in West Africa, six (ICMR 157001, ICMR 157002, ICMR 157003, ICMR 157004, ICMR 157005, ICMR 167011) different restorer lines that restorer's fertility of two or more CMS of pearl millet were utilised as parents. There parents differ in their agronomic as well as in morphological traits and good at fertility restoration, were crossed in a full diallel mating design at ICRISAT, Sahelien center, Niamey, Niger to generate thirty (30) F_1 crosses, during the off season (Annexure 2). These 30 F_1 crosses along with their 6 parents (36 genotypes in total) were evaluated in rainy season 2017 ICRISAT, Sahelien center.

Objective 3 and 4: Eighteen male sterile lines with different CMS viz., ICMA 08888, ICMA 177001, ICMA 177002, ICMA 177004, ICMA 177090, and ICMA 177111 (A_1 CMS) ICMA 177003, ICMA 177005, ICMA 177006, ICMA 177007 (A_4 CMS), ICMA 177011, ICMA 177012, ICMA 177013, ICMA 177015, ICMA 177020, ICMA 177021, ICMA 177022, ICMA 177029 (A_5 CMS) were crossed with seven good fertility restorer lines as male or pollen parent viz., ICMR 08666, ICMR 08777, ICMR 08888, ICMR 09666, ICMR 09999, ICMR 1301, and ICMR 167011 to produce 126 single cross hybrids in off season 2017 at ICRISAT, Sahelian centre, Niamey, Niger. These hybrids have been tested for fertility/sterility in rainy season 2017. Sixty-six (66) fertile single cross hybrids have been identified for commercial purpose and was used in multilocation testing for adaptability and stability.

Identified adapted open pollinated varieties from West and Central Africa (16 OPVs) viz., ICMV IS 89305, ICMV IS 90305, ICMV IS 92222, ICMV IS 94206, ICMV IS 99001, ICMV 167002, Ankoutess, Chakti, Exbornu, Gamoji, GB 8735, Jirani, PPB Falwel, PPB Serkin Haoussa, Zango Badau and Zatib available at ICRISAT Sahelian center, Niger are crossed with 10 A lines to maxinizing the change to get fertile hybrids viz., ICMA 04999 (A_5 CMS), ICMA 177001, ICMA 177002, ICMA 177003, ICMA 177004, ICMA 177005, ICMA 177006, ICMA 177007, ICMA 177090 and ICMA 177111 to produce 160 top cross hybrids in off season 2016 at ICRISAT, Sahelian center, Niamey, Niger. These hybrids have been tested for fertility/sterility in rainy season 2016 and off season 2017 to confirm their fertility. Among them, 42 fertile top cross hybrids have been identified for commercial propose and have been used in the multilocation testing for adaptability and stability.

2.3. Methods

2.3.1. Experimental layout

The experimental layout was a randomizing complete bloc design with 3 replications for the restorer's improvement and 2 replications for the remining trials. Each plot had 3 m length with 75 cm distance between rows and 20 cm between plants except for the restorer's improvement sowed on 4.2 m length and 80 cm between plants. All the trials except the restorer's improvement (conducted in rainy season 2017), have been conducted in rainy season 2018.

The 108 hybrids obtained from line x testers design and their 21 (9 lines and 12 testers) parents were evaluated in two locations of West Africa, ICRISAT, Sadore (Niger) and Gampela (Burkina Faso). While, the thirty F_1's crosses generated from the diallel cross along with their six parents were evaluated at ICRISAT, Sadore, Niger.

One hundred and twelve (112) genotypes comprising of 66 single cross hybrids, 42 top cross hybrids and 4 checks (2 OPVs, CHAKTI, ICMV 167005 and 2 single cross hybrids (ICMH 1201, ICMH 1301) were evaluated in three locations; Sadore (Niger), Gampela (Burkina Faso) and Cinzana (Mali) of West Africa. The commercial heterosis was estimated in each location and across the locations using the mean value of grain yield, grain iron (Fe) and zinc (Zn) content as the percentage of increase or decrease of hybrids over the two OPVs (CHAKTI and ICMV 167005). The stability and adaptability were recorded also for grain yield, grain iron content and grain zinc content.

The two checks are different in all the traits under the study. The check CHAKTI is early maturing (60 days), medium height, short panicle and is biofortified OPVs with more than 65 mg/kg Iron and Zinc. While the check ICMV is late maturing variety (95days), tall, long panicle with high grain yield potential (around 2t/ha) compared to CHAKTI (1.2 t/ha), but low in iron and zinc (less than 40 ppm). Then compare the hybrids to their different OPVs is useful to determine the hybrids which combine high yield with grain iron and zinc content.

Overplanted plots were thinned at one plant per hill at 15 days after sowing. Hand weeding was carried out when necessary. A basal dose of fertilizer, 100 kg/ha was applied to the field at the land preparation stage. Micro dosing of the crop with urea, 2g per hill was carried out at 30 days after seedling emergence (DAE). The recommended packages of practices were followed during entire crop season to grow good crop by following Stephen et al (2015). Data were recorded for days to 50% flowering, plant height, panicle length (cm), panicle circumference (cm), panicle weight (g/plot), grain weight (g/plot) and biomass weight (g/plot). Grain yield (t/ha) and biomass yield (t/ha), was computed using primary data.

2.3.2. Seed production of identified single and top cross hybrids

The seed of identified single (66) and top cross (42) hybrids has been produced in isolation (using the same pollen parent with different A lines though the ratio 6: 2) as well as by hand pollination in off season 2018 at ICRISAT, Sahelien center, Niamey, Niger. Then, their 108 hybrids plus two other single cross hybrids (ICMH 1201 and ICMH 1301) from ICRISAT India and two improved OPVs as checks (CHAKTI and ICMV 167005) (Annexe 3) were used for the commercial heterosis, adaptability and stability studies.

2.3.3. Observation recorded

2.3.1.1. Days to 50 percent flowering

Fifty percent flowering was recorded in all the trials as number of days taken from sowing to the stigma emergence in 50% of the main shoots in a plot number (number of days until 50% of the main stems in a plot show female stigmas).

2.3.1.2. Plant height (cm)

The height as measured from the ground level to the tip of the main panicle was recorded on three plants randomly in each replication at the time of harvest with help of measurement rod and expressed in centimeters. Then the mean of the three plants are calculated for each replication and used for the analysis. This trait was recorded in all trials.

2.3.1.3. Panicle length (cm)

The length of the panicle of the main plant was measured on three panicles of three different plants selected randomly in each replication from the base to the tip of the panicle at maturity and expressed in centimeters. The mean of the three panicles are calculated for each replication and used for the analysis as the panicle length value in the replication. This trait was recorded in all trials.

2.3.1.4. Panicle circumference (cm)

The circumference of the main stalk panicle was measured on three panicles from three different plants selected randomly in each replication from the middle of the panicle at maturity and expressed in centimeters. The mean of the three panicles was considered as the panicle circumference in the replication and used for the analysis. This trait was recorded in all trials.

2.3.1.5. Grain yield (t/ha)

After threshing, grains obtained from all productive tillers of an individual plot at optimum moisture level was weighed and recorded. Plot yield converted into yield t/ha by using the following formula:

$$\text{Grain yield (t/ha)} = ((\frac{\mathrm{X} \times 10000}{\mathrm{plot\ size}})/1000)/1000)$$

Where X = grain weight by plot (g) and plot size (m)

This trait was recorded in all trials.

2.3.1.6. Biomass yield (t/ha)

The biomass obtained from individual plot at optimum dry level was weighed and recorded. Plot yield converted into yield t/ha by using the following formula:

$$\text{Biomass yield (t/ha)} = ((\frac{\mathrm{X} \times 10000}{\text{plot size}})/1000)/1000)$$

Where X = biomass weight by plot (g) and plot size (m)

This trait was recorded only in restorer's improvement trial.

2.3.2. Data analysis

2.3.2.1. Analysis of variance (ANOVA)

The analysis of variance for all characters under the study as well as Additive Main Effects and Multiplicative Interaction (AMMI) for grain yield, grain Fe and Zn content were carried out for individual trial as well as for pooled analysis using GenStat® 18^{th} edition (GenStat, 2015). Significance of the differences between the genotypes was judged by F-test, while the genotypic means were compared by least significant difference (LSD) at $P \leq 0.01$ and $\mathrm{P} \leq 0.05$.

2.3.2.2. Analysis of combining ability and genetic expectation

2.3.2.2.1. ANOVA for combining ability and genetic expectation

The diallel and line × tester analysis were carried out for individual trial (diallel) as well as for across locations (line × tester) to test parents and crosses with respect to their general and specific combining ability, respectively, following Method I, and Model 2 of Griffing (1956) and Kempthorne (1957) using respectively AGD-R (Analysis of Genetic Designs in R), Version 5.0 (Francisco *et al*, 2015) and OPSTAT (Sheoran, 2013). The mean squares due to different sources of variation as well as their genetic expectation and variance were estimated for individual trial (diallel) as well as for across locations (line × tester) were also estimated from the analysis of variance.

2.3.2.2.2. Estimating general combining ability and specific combining ability variance and effects

The general combining ability (*gca*) and specific combining ability (*sca*) variance and effets were estimated from their respective mean squares obtained from the analysis of variance using AGD-R (Analysis of Genetic Designs in R), Version 5.0 (Francisco *et al*, 2015) (diallel) and OPSTATA (L × T).

2.3.2.2.3. Testing significant of combining ability effects

The significant of combining ability effects was tested following Singh and Chaudhary. (1985) using the standard errors pertaining to *gca* effect of line and tester and *sca* effects of crosses generated from AGD-R (Analysis of Genetic Designs in R), Version 5.0 (Francisco *et al,* 2015) for the diallel analysis and OPSTAT for the line x tester one.

2.3.2.2.4. Predictability ratio and heritability

The predictability ratio (PR) was computed following Govindaraj *et al.* (2013) using the general combining ability (GCA) and specific combining ability (SCA) variance. Heritability estimates were calculated according to Johnson et al. (1955). All data for predictability and heritability were generated from AGD-R (Analysis of Genetic Designs in R), Version 5.0 (Francisco *et al*, 2015) (diallel) and OPSTAT (Sheoran, 2013) (line x tester).

2.3.2.3. Estimating of heterosis

The magnitude of heterosis, expressed as the percentage of increase or decrease of a character over mid-parent and better parent, was estimated following Fonseca and patterson (1968) and Liang *et al.* (1972). While, the commercial heterosis was estimated over CHAKTI and ICMV 167005 following the formula suggested by Meredith and Bridge (1972).

2.3.2.3.1. Mid-parent heterosis (MPH)

The mid-parent heterosis (MPH) was estimated as the percentage deviation of the mean performance of F1 over the mean mid-parent value.

$$\text{MP heterosis (\%)} = \frac{\text{F1}-\text{MP}}{\text{MP}} \times 100$$

Where F1 = mean value of the hybrid and MP = mean of the two parents.

2.3.2.3.2. Better parent heterosis (BPH)

The better parent heterosis (BPH) was estimated as the percentage deviation of the mean performance of F_1 over the better parent mean value.

$$\text{BP heterosis (\%)} = \frac{\text{F1}-\text{BP}}{\text{BP}} \times 100$$

Where F_1 = mean value of the hybrid and BP = mean of the better parents.

2.3.2.3.3. Commercial heterosis (CH)

The commercial heterosis was estimated as the percentage deviation of the mean performance of F1 over improved OPVs (CHAKTI and ICMV 167005).

$$\text{SH }(\%) = \frac{\text{F1}-\text{OPV}}{\text{OPV}} \times 100$$

Where F_1 = mean value of the F1 hybrid and OPVs = mean value of the Open pollinated variety.

2.3.2.4. Correlation analysis

Association of agronomic and morphological traits in all the trials was estimated though the means values of characters using GenStat® 18th edition (GenStat, 2015).

The significance of the correlation coefficient was tested by referring to the standard table given by Snedecor GW and Cochran WG. (1967).

2.3.2.5. Stability and adaptability

The stability and adaptability of the genotypes (112 hybrids and 2 checks) across the three environments were determined using Additive Main Effect and Multiplicative Interaction (AMMI) model in GenStat 18 (GenStat, 2015). AMMI stability value (ASV) was calculated for each genotype according to the relative contributions of the principal component axis scores (IPCA1 and IPCA2) to the interaction sum of squares following Purchase *et al.* (2000).

Then in AMMI biplot analysis method to find the G × E interaction for grain yield, grain iron (Fe) and zinc (Zn), the mean of genotypes which are greater than grand mean and PCA scores almost zero considered as a general adaptability over the environment. In AMMI biplot also, the genotypes with high mean performance and large value of IPCA scores are conceived as specific adaptability to environment (Adjebeng-Danquah *et al,* 2017; Sumathi *et al,* 2017).

However, the quantitative measure of stability will not be provided by AMMI analysis, therefore, Purchase *et al.* (2000) proposed an AMMI Stability Value (ASV) measure as follow:

$$ASV = \sqrt{\left[\frac{IPCA1_{sumofsquae}}{IPCA2_{sumofsquae}}\left(IPCA1_{score}\right)\right]^2 + \left(IPCA2_{score}\right)^2}$$

to quantify and classify genotypes according to their *per se* potential.

Where IPCA1Sum of squares/IPCA2Sum of squares is the weight given to the IPCA1-value by dividing the IPCA1 sum of squares (from the AMMI analysis of variance table) by the IPCA2 sum of squares. ASV is the distance of the varieties from point zero of the scatter diagram (IPCA1 vs. IPCA2) (Sumathi *et al,* 2017). Then, Smaller ASV scores indicate a more stable genotype across environments (Adjebeng-Danquah *et al,* 2017; Sumathi *et al,* 2017). Stability index (SI) was also calculated using the sum of the ranking based on yield and ranking based on the AMMI stability value following Adjebeng-Danquah *et al.* (2017).

$$\mathbf{YSI = RASV + RY,}$$

Where RASV is the rank of the genotypes based on the AMMI stability value;
RY is the rank of the genotypes based on yield across environments (RY).
YSI incorporates both mean yield and stability in a single criterion. Then, low values of both parameters show desirable genotypes with high mean yield and stability (Tumuhimbise *et al,* 2014; Bose *et al,* 2014).

2.3.2.6. Grain sample analysis for iron (mg/kg) and zinc (mg/kg) contents

Open-pollinated grain samples of each replication in each trial were analysed for grain iron (mg/kg) and zinc (mg/kg) contents under lab conditions using X-Ray Fluorescence (XRF) machine following Govindaraj *et al.* (2016) and Paltridge *et al.* (2012). (Figure 1).

Figure 1. ED-XRF at ICRISAT Sahelian Center, Niamey, Niger for grain micronutrient analysis

CHAPTER III: RESULTS

3.1. Combining Ability and Heterosis for Agronomic Traits and Grain Quality in Pearl Millet (*Pennisetum glaucum* L.) for Hybrid Breeding at Sadore and Gampela

3.1.1. Genetic Variability

Analysis of variance for individual as well as across locations showed significant differences ($P \leq 0.05$ and $P \leq 0.01$) among the hybrids for almost all the traits, indicating presence of significant variability in the tested genotypes (Table 2).

Analysis of variance showed that differences among the parental lines and among the crosses in the two locations were highly significant ($p < 0.01$) for all the traits (Table 2). Differences among lines and testers were highly significant ($p < 0.01$) in the two environments. But in Sadore (Niger) the mean squares of testers (male) was high than the mean squares of lines (female) for all the traits except for panicle length and panicle circumference. While in Gampela (Burkina) the testers mean squares were higher than the mean squares of lines for the panicle circumference and grain Fe content.

The line x tester interaction was highly significant ($p < 0.01$) for all traits except for Fe and Zn at Sadore and except for panicle length, grain yield and grain Fe at Gampela (Table 2). The relative contribution of line x tester interaction, however, was greater than those of lines and testers for plant height and panicle circumference but much smaller than those of lines and testers for grain Fe in both environments. Environmental effect was only significant ($p < 0.05$) on the two micronutrients (Fe and Zn) in both trials.

The mean squares among parents' $_{vs}$ hybrids was highly significant for all studied traits across environments except for grain Fe and Zn content at Gampela.

Table 2. Analysis of variance showing the mean sum of squares of L × T analysis of pearl millet genotypes at Sadore and Gampela.

Source of Variation	DF	Days to 50% flowering		Plant height		Panicle length		Panicle circumference		Grain yield		Grain Fe content		Grain Zn content	
		Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela
Replication	1	11.30	120.06	2974.33	4529.31	19.54	18.45	0.02	1.55	0.57	0.19	10.81	14.54	8.62	30.22
Genotypes	128	61.41**	44.00**	3772.75**	3596.56**	71.49**	68.59**	2.63**	3.13**	0.84**	1.06**	64.88**	62.12**	31.95**	48.99**
Parents	20	74.77**	44.16**	1976.93**	1648.38**	85.68**	63.38**	4.26**	3.85**	0.51**	0.21**	108.45**	93.69**	55.34**	65.01**
Males	11	73.49**	27.77**	2135.13**	1416.67**	77.57**	44.22**	3.71**	3.59**	0.58**	0.08**	151.14**	100.02**	74.27**	38.07**
Females	8	73.00**	67.01**	1035.18**	1655.89**	93.25**	92.14**	4.18**	2.89**	0.34**	0.40**	63.31**	94.82**	35.14**	99.04**
Male vs Female	1	103.14**	41.72**	7770.72**	4137.18**	114.29**	44.05^{NS}	10.87**	14.34**	1.15**	0.06^{NS}	0.02^{NS}	15.04^{NS}	8.64^{NS}	89.01**
Crosses	107	36.27**	25.10**	2414.49**	2389.48**	50.60**	56.01**	1.92**	2.64**	0.48**	0.95**	57.00**	56.55**	27.03**	46.41**
Parents vs. Crosses	1	2483.12**	2062.87**	185023.43**	171718.63**	2023.16**	1518.46**	46.41**	40.67**	45.45**	29.73**	35.93*	26.71^{NS}	91.06**	5.30^{NS}
Error	128	8.13	8.11	282.97	292.30	8.52	19.51	0.81	0.77	0.04	0.03	7.73	7.49	7.29	8.86

** F probability significant at P 0.01; NS, non-significant mean sum of squares

3.1.2. Analysis of variance for combining ability and genetic components

Analysis of variance for combining ability studies showed significant mean sum of squares due to males for all the studied traits in both the locations (Table 3). Mean sum of squares due to females were found significant for all the traits in the two locations while the mean sum of squares of females for grain Fe content at Gampela and for grain Zn at Sadore, were non-significant. Mean sum of squares due to the interaction of male × female was found significant for all the traits except for panicle circumference across locations and for panicle length at Gampela.

Perusal of Table 2 indicated that the variance due to GCA (σ^2GCA) was higher as compared to variance due to SCA (σ^2SCA) for number of days to 50% flowering, plant height, panicle length (except Sadore) and panicle circumference, while the σ^2GCA was lower as compared to σ^2SCA for grain yield, grain Fe and Zn contents over the two environments. The predictability ratio was high for number of days to 50% flowering (0.70 and 0.75 at Sadore and Gampela, respectively), plant height (0.80 and 0.81), panicle length (0.66 and 0.87) and panicle circumference (0.91 and 0.96) at both the locations. The predictability ratio is low for grain yield (0.31 and 0.58) and grain Fe (0.57 and 0.39) and Zn (0.35 and 0.18) contents.

The proportional contribution of lines, testers and their interaction to total variance (%) across environments showed maximum contribution of lines to total variance for plant height (61.25% and 57.05%) followed by panicle circumference (47.13% and 49.05%) (Table 3). The contribution of tester to total variance was not maximum for any trait and the line × tester interaction displayed maximum contribution to total variance for number of days to 50% flowering (39.08% and 43.41%), panicle length (39.83% and 40.35%), grain Fe content (42.27% and 53.56%) and grain Zn content (60.92% and 70.91%) across environments. For grain yield, the maximum contribution to total variance was displayed by the line × tester interaction (61.03%) at Sadore whereas it was displayed by line (44.87%) at Gampela.

Table 3. Estimates of combining ability mean sum squares, genetic components and proportional contribution of lines, testers and their interactions to total variance (%) of pearl millet at Sadore and Gampela.

Source of Variation		Days to 50% flowering		Plant height		Panicle length		Panicle circumference		Grain yield		Grain Fe content		Grain Zn content	
	DF	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela	Sadore	Gampela
Blocks	1.00	20.17	102.78	3166.34	4704.00	36.67	16.67	0.01	1.85	0.61	0.17	8.01	17.61	14.13	20.20
Due to Males	11.00	104.22**	66.68**	14385.13**	13259.34**	140.94**	173.67**	8.79**	12.61**	0.75*	4.15**	221.42**	209.87**	75.13**	70.35*
Due to Female	8.00	152.24**	98.29**	4405.83**	5823.08**	213.45**	208.04**	5.76**	8.33**	1.47**	2.37**	135.70**	62.66^{NS}	37.96^{NS}	83.85*
Male × Female	88.00	17.24**	13.25*	737.12**	718.60**	24.51**	27.48^{NS}	0.71^{NS}	0.88^{NS}	0.356**	0.42**	29.30**	36.83**	20.02**	40.02**
Error	107.00	8.20	8.84	320.53	331.99	9.49	22.68	0.83	0.80	0.04	0.03	8.23	7.50	7.25	8.74
Genetics components															
COV(HS)		5.29	3.30	412.30	420.12	7.27	7.78	0.31	0.46	0.04	0.14	7.11	4.74	1.74	1.77
COV(FS)		15.09	8.80	1032.91	1033.55	22.05	17.96	0.57	0.96	0.23	0.47	24.75	24.14	9.87	19.17
σ^2GCA		5.29	3.30	412.30	420.12	7.27	7.78	0.31	0.46	0.04	0.14	7.11	4.74	1.74	1.77
σ^2SCA		4.52	2.21	208.30	193.30	7.51	2.40	0.06	0.04	0.16	0.20	10.54	14.67	6.39	15.64
PR		0.70	0.75	0.80	0.81	0.66	0.87	0.91	0.96	0.31	0.58	0.57	0.39	0.35	0.18
σ^2A		21.14	13.19	1649.21	1680.50	29.08	31.12	1.25	1.83	0.14	0.54	28.43	18.94	6.96	7.06
σ^2D		18.08	8.82	833.20	773.21	30.03	9.61	-0.24	0.17	0.63	0.79	42.14	58.66	25.55	62.56
% Contribution of line		29.54	27.31	61.25	57.05	28.63	31.88	47.13	49.05	16.04	44.87	39.93	38.15	28.58	15.58
% Contribution of tester		31.38	29.28	13.64	18.22	31.54	27.77	22.47	23.57	22.94	18.64	17.80	8.28	10.50	13.51
% Contribution of line × tester		39.08	43.41	25.11	24.73	39.83	40.35	30.40	27.38	61.03	36.50	42.27	53.56	60.92	70.91
SE of GCA of lines		0.55	0.57	3.45	3.51	0.59	0.92	0.18	0.17	0.04	0.03	0.55	0.53	0.52	0.57
SE of GCA of testers		0.65	0.67	4.04	4.11	0.70	1.08	0.21	0.20	0.05	0.04	0.65	0.62	0.61	0.67
SE of SCA of crosses		1.83	1.90	11.43	11.63	1.97	3.04	0.58	0.57	0.13	0.11	1.83	1.75	1.72	1.89

*,** F value significant at P 0.05 and 0.01, respectively; NS, non-significant mean sum of squares; PR, predictability ratio;σ^2GCA, variance due to general combining abiltiy; σ^2SCA, variance due to specific combining abiltiy; HS, half sibs; FS, full sibs; σ^2A, additive variance; σ^2D, dominance variance; SE, standard error

3.1.3. Parental Performance *Per se* and General Combining Ability

Mean performance of parents (lines and testers) and their *gca* effects across environments were presented in Table 4. Number of days to 50% flowering varied from 56.00 to 75.00 days among the lines and from 53.00 to 73.00 days among the testers at Sadore (Niger) whereas, it varied from 57.00 to 73.00 days among the lines and from 55.00 to 69.00 days among the testers at Gampela. The lines ICMB 177001, ICMB 177003 and ICMB 177111 and the testers Exbornu, ICMR 1301, ICMR 157004, ICMR 167011, ICMR IS 16006, ICMR IS 16007, ICMR IS 16008 exhibited early flowering than their respective overall mean in both the locations. Two lines, ICMB 177004 and ICMB 177007 which were not earlier than the grand mean had significant and negative *gca* effects, whereas, the testers ICMR 1301 and ICMR IS 16007 showed earlier flowering with significant and negative *gca* effects for days to 50% flowering. The lines ICMB 177002, ICMB 177005, and the testers Exbornu, ICMR 08777exhibited significant and positive *gca* effects for days to 50% flowering across locations.

The range of plant height varied from 72.50 to 154.50 cm and from 97.00 to 202.50 cm among the lines and testers, respectively at Sadore (Niger) whereas, it varied from 65.00 to 167.50 cm and from 82.50 to 182.00 cm among the lines and testers, respectively at Gampela (Table 4). The lines ICMB 177001, ICMB 177002 and ICMB 177111 and the testers Exbornu, ICMR 157003 and ICMR 157004 had plant height greater than the overall mean in both locations. The lines ICMB 177002 and ICMB 177111 and the testers Exbornu, ICMR 08666, ICMR 08777, ICMR 08888, ICMR 09666, ICMR 157003 and ICMR 157004 had exhibited significant and positive *gca* effects across locations.

Panicle length ranges from 21.50 to 42.50 cm and 20.00 to 40.00 cm for lines and testers, respectively at Sadore. The range of 16.00 to 38.50 cm and from 22.50 to 37.00 cm for lines and testers, respectively at Gampela (Table 4). The genotypes ICMB 177001, ICMB 177002, ICMB 177005 ICMB 177090, ICMR 167011, ICMR IS 16006, ICMR IS 16007 and ICMR IS 16008 showed greater panicle length than the overall mean across location. Among their genotypes, ICMB 177002, ICMB 177090, ICMR 157003 and ICMR IS 16008 had highly significant and positive *gca* effects for panicle length across locations. The range of mean performance of parents for panicle circumference varied from 5.50 to 10.50 cm among lines and from 6.00 to 10.50 cm among testers, respectively at Sadore, whereas, it varied from 6.00 to 10.00 cm among lines and from 7.00 to 11.00 cm among testers, respectively at Gampela. ICMB 177111, ICMR 08666, ICMR 08777 and ICMR 1301showed panicle circumference greater than the overall means. The line ICMB 177111 and the testers ICMR 08666, ICMR

08777 and ICMR 157003 had shown significant and positive *gca* effects for panicle circumference across locations.

The grain yield range varied from 0.34 to 1.65 t/ha among lines and from 0.40 to 2.12 t/ha among testers at Sadore (Table 4). At Gampela, the range was 0.41 to 1.69 t/ha among lines and from 0.45 to 1.17 t/ha among the testers. The line ICMB 177111 and the testers Exbornu, ICMR 09666, ICMR 157004 and ICMR IS 16008 showed means greater than the overall mean across locations. ICMB 177005, ICMB 177111, ICMR 08666, ICMR 08777, ICMR 157003 and ICMR 157004 had significant and positive *gca* effects for grain yield across locations.

The grain Fe and Zn content varied from 32.48 to 50.13 mg kg^{-1} and from 28.43 to 40.35 mg kg^{-1} among the lines and from 34.75 to 61.77 mg kg^{-1} and from 30.50 to 51.50 mg kg^{-1} among the testers, respectively at Sadore (Table 4). Whereas, the range of 35.75 to 54.65 mg kg^{-1} and 32.00 to 50.98 mg kg^{-1} among the lines and from 35.75 to 63.50 mg kg^{-1} and 30.50 to 46.58 mg kg^{-1} among the testers, for grain Fe and Zn respectively at Gampela. The genotypes ICMB 177001, ICMB 177004, ICMB 177005, ICMB 177007, ICMR 08666, ICMR 08777 and ICMR 1301 had shown means greater than the overall means for grain Fe content across location. Among the lines ICMB 177003 showed positive and significant *gca* effects for grain Fe content across locations whereas among the testers, ICMR 08666 and ICMR 1301 showed significant and positive *gca* effects for grain Fe content across locations. The parents ICMB 177004, ICMB 177007, ICMR 08666, ICMR 08777, ICMR 09666 and ICMR 1301 showed means values of grain Zn content greater than the overall means across locations. The line ICMB 177001 and the testers ICMR 08666 and ICMR 1301 showed positive and significant *gca* effects for grain Zn content across locations.

Table 4. Mean performance of parents and their general combining ability (*gca*) effects of pearl millet at Sadore and Gampela.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA
Line																
ICMB 177001	58.00	-1.79**	57.00	-0.12	110.00	4.41	103.50	5.17	36.00	1.40**	37.50	1.00	6.50	-0.38	6.00	-0.11
ICMB 177002	67.50	3.63**	69.50	3.17**	117.50	10.12**	105.50	20.42**	33.50	3.40**	38.50	3.29**	7.50	-0.17	7.00	-0.07
ICMB 177003	58.00	-0.20	56.50	0.21	97.50	-4.93	110.00	-9.25**	30.50	1.90**	32.00	0.83	7.00	0.33*	8.00	-0.19
ICMB 177004	65.50	-1.83**	58.50	-1.29*	72.50	-18.68**	101.00	-15.25**	28.50	-1.31*	34.00	-3.00**	7.50	0.08	7.00	0.31*
ICMB 177005	66.00	2.13**	61.50	2.55**	95.50	-5.34	77.50	-0.79	35.50	0.69	32.00	0.25	5.50	-0.58**	6.00	-0.65**
ICMB 177006	74.50	2.88**	73.00	0.84	95.00	-0.63	95.00	-3.62	29.50	-0.01	32.50	1.96*	6.50	-0.17	7.00	-0.49**
ICMB 177007	58.00	-4.12**	63.50	-3.45**	92.00	-14.43**	65.00	-21.20**	21.50	-2.76**	16.00	-3.00**	6.00	0.08	7.00	0.01
ICMB 177090	63.50	-1.04*	63.00	-0.79	97.50	2.45	86.50	-2.16	42.50	2.74**	36.00	3.46**	6.50	-0.29	7.50	-0.19
ICMB 177111	56.00	0.34	57.50	-1.12*	154.50	27.03**	167.50	26.67**	21.50	-6.06**	27.50	-4.79**	10.50	1.08**	10.00	1.39**
Tester																
Exbornu	58.50	4.21**	59.00	2.64**	202.50	12.42**	144.00	11.94**	25.00	-0.51	32.50	3.56**	6.00	0.60**	8.50	0.25
ICMR 08666	64.00	0.10	64.00	1.26*	110.00	13.03**	120.00	17.05**	22.00	-2.51**	25.50	-3.83**	9.00	0.82**	10.00	1.14**
ICMR 08777	72.50	4.16**	69.00	2.98**	110.00	15.87**	99.00	23.10**	20.50	-3.07**	25.50	-3.78**	10.00	1.21**	11.00	1.53**

ICMR 08888	68.50	-1.40*	60.50	-2.02**	120.00	10.59**	118.50	9.88**	24.00	1.26*	28.50	0.83	6.00	-0.29	7.50	-0.81**
ICMR 09666	63.00	-1.68**	62.00	0.31	127.50	16.26**	132.00	8.27*	24.50	0.26	27.50	-0.11	7.50	-0.18	8.50	0.14
ICMR 1301	52.50	-4.29**	55.00	-4.02**	117.50	14.98**	105.00	1.99	20.00	-4.85**	22.50	-5.17**	10.50	0.60**	10.50	0.31
ICMR 157003	56.50	-0.34	62.50	-0.69	160.00	37.92**	147.50	33.05**	29.00	3.82**	24.50	4.89**	8.00	0.49*	8.00	0.69**
ICMR 157004	56.00	-0.34	58.50	-0.41	182.50	26.26**	182.00	32.55**	27.00	-2.07**	34.00	-1.11	8.50	-0.68**	7.00	-0.03
ICMR 167011	58.00	1.38*	59.00	-0.08	97.50	-39.69**	82.50	-29.07**	40.00	3.71**	37.00	0.39	8.00	-0.63**	7.00	-0.92**
ICMR IS 16006	58.50	0.55	57.50	0.87	110.00	-34.47**	112.00	-32.90**	32.00	0.43	31.00	0.83	8.50	-0.85**	7.50	-0.47**
ICMR IS 16007	57.00	-1.57**	57.50	-1.19*	115.00	-41.47**	105.50	-40.29**	34.50	0.04	35.50	0.17	7.50	-0.63**	8.00	-0.81**
ICMR IS 16008	53.00	-0.79	58.00	0.37	120.00	-31.69**	108.00	-35.57**	33.50	3.49**	32.50	3.33**	7.50	-0.46*	8.00	-1.03**

*,** t test significant at P 0.05 and 0.01, respectively

Table 4 cont'd. Performance per se and grain nutrient concentration of lines and testers and their general combining ability (*gca*) effects of pearl millet at Sadore and Gampela.

Genotype	Grain yield (t/ha)				Grain Fe content (ppm)				Grain Zn content (ppm)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA
Line												
ICMB 177001	0.34	-0.34**	0.50	-0.15**	50.13	1.84**	54.65	0.80	33.25	1.56**	46.78	1.45**
ICMB 177002	0.49	0.32**	0.68	0.05	32.48	0.66	43.50	0.71	30.78	-0.02	37.05	1.65**
ICMB 177003	0.51	0.05	1.69	-0.11**	46.18	4.16**	44.75	1.63**	38.98	2.57**	37.03	-0.12
ICMB 177004	0.34	-0.15**	0.93	-0.15**	43.40	-0.29	53.63	2.12**	40.35	-1.21**	50.98	2.96**
ICMB 177005	0.45	0.12**	0.41	0.12**	41.45	-2.76**	52.68	-0.63	33.78	-0.42	49.40	-0.43
ICMB 177006	0.41	-0.04	0.43	-0.05	35.98	-1.17*	41.50	0.31	30.85	-0.55	35.50	0.79
ICMB 177007	0.70	-0.36**	0.67	-0.41**	42.55	2.03**	52.40	-0.05	38.15	-0.14	46.40	-1.65**
ICMB 177090	0.75	0.11**	0.41	-0.04	37.23	-2.93**	35.75	-2.13**	31.50	-0.94*	32.00	-2.21**
ICMB 177111	1.65	0.29**	1.26	0.74**	36.10	-1.53**	40.45	-2.76**	28.43	-0.84	36.35	-2.44**
Tester												
Exbornu	1.10	0.02	0.78	0.54**	34.75	-2.02**	41.70	-0.35	32.54	-1.58*	38.58	-0.82
ICMR 08666	0.45	0.23**	0.59	0.14**	53.73	4.04**	53.68	4.37**	40.13	2.58**	41.83	2.50**
ICMR 08777	0.66	0.15**	0.58	1.16**	43.25	3.10**	44.88	0.18	38.43	-0.82	43.23	1.94**
ICMR 08888	0.40	0.07	0.45	-0.17**	37.50	3.05**	40.75	-0.56	31.00	0.64	35.50	2.35**
ICMR 09666	1.16	-0.11*	0.86	-0.42**	35.50	-3.20**	43.40	-2.13**	35.63	-1.54*	39.50	-1.21*
ICMR 1301	0.53	-0.13**	0.42	-0.09*	61.77	7.32**	63.50	8.78**	51.50	5.35**	46.58	3.00**
ICMR 157003	1.82	0.28**	0.62	0.25**	33.68	-0.32	46.63	-0.57	30.50	-0.04	40.30	-1.09
ICMR 157004	2.12	0.30**	1.17	0.11**	34.90	-2.79**	41.53	-4.00**	31.63	-0.87	37.15	-2.69**
ICMR 167011	0.83	-0.22**	0.76	-0.36**	38.50	-3.43**	43.78	-1.64**	31.50	-1.31*	36.23	-1.15*
ICMR IS 16006	0.91	-0.14**	0.61	-0.28**	38.35	-2.60**	44.98	-2.59**	34.00	-0.89	37.13	-1.85**
ICMR IS 16007	0.57	-0.30**	0.71	-0.43**	40.98	-0.88	44.00	-0.41	31.73	-0.39	33.50	0.68
ICMR IS 16008	0.98	-0.16**	0.85	-0.46**	33.98	-2.26**	35.75	-1.08*	30.50	-1.13	30.50	-1.65**

*,** t test significant at P 0.05 and 0.01, respectively

Correlation studies

Positive correlations have been found between performance *per se* of parents and their *gca* effects for all the traits except tester/*gca* for grain yield at Gampela (Table 5). Similarly, positive correlations were observed between the crosses and their *sca* effects. Nevertheless, the significance of correlation were a function of traits and locations. Thus, the correlation among the hybrids and their *sca* effects for days to 50% flowering was significant both at Sadore and Gampela whereas it was significant for line/*gca* at Sadore and for tester/*gca* at Gampela.

Regarding plant height, the correlation was significant among line/*gca* across locations and significant for tester/*gca* at Gampela (Table 5). It was significant at Sadore as well as at Gampela for line/*gca* and cross/*sca* and significant for tester/*gca* along at Sadore for panicle length. For panicle circumference it was significant for line/*gca* at Sadore and Gampela and for tester/*gca* at Gampela.

The correlation among cross/*sca* was positive and significant for grain yield, grain Fe and Zn at Sadore and Gampela (Table 5). While the correlation for Fe among tester/*gca* was significant at Sadore and gampela and significant for Zn at only Sadore.

Relationship between grain yield, grain Fe and Zn densities *per se* performance of crosses and mid parent values as the measure of gene action across the two locations, had showed significant and positive correlations for grain yield (r=0.26**) (Figure 2), grain Fe (r=0.61**) and Zn contents (r=0.38**) (Figure 3).

Association of agronomic and morphological traits across locations revealed highly significant and negative correlations between days to 50% flowering and plant height (r = -0.35**), panicle length (r = -0.16*), panicle circumference (r = - 0.16*) and grain yield (r= -0.23**) whereas it was negative and non significative with grain Fe and Zn (Annexe 2). Significant positive correlations were seen between plant height and panicle length (r = -0.20**), panicle circumference (r = 0.46**) and grain (r = 0.66**) yield. Significant and positive correlation was seen between the grain yield and panicle circumference (r = 0.40**). Positive and significant correlation of r = 0.76** was observed between grain Fe and Zn contents. The grain Fe content exhibited significant and negative association with grain yield (r = -0.19*) and positive correlation with panicle circumference (r = 0.19*).

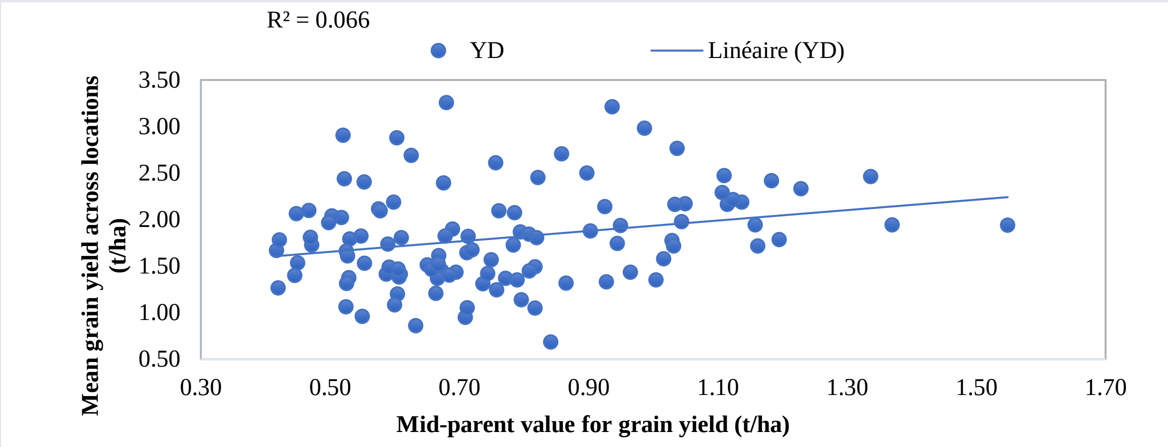

Figure 2. Relationship for grain yield between mid-parent and crosses means values in line × tester trial at Sadore and Gampela

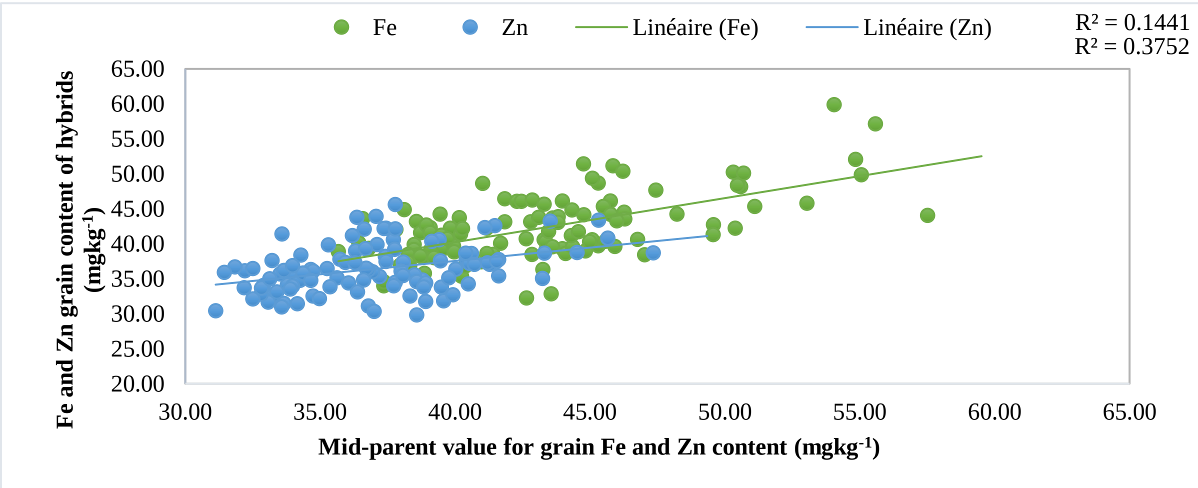

Figure 3. Relationish for grain Fe and Zn content between mide-parent and crosses means values in line × tester trial at Sadore and Gampela

Table 5. Correlation among the means of lines, testers and crosses, their general combining abiliy (*gca*) and specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Traits	Days to 50% flowering		Plant height		Panicle length		Panicle circumference		Grain yield		Grain Fe content		Grain Zn content	
Location	**Sadore**	**Gampela**	**Sadore**	**Gampela**	**Sadore**	**Gampela**	**Sadore**	**Gampela**	**Sadore**	**Gampela**	**Sadore**	**Gampela**	**Sadore**	**Gampela**
Line/*gca*	0.65*	0.37	0.96**	0.73*	0.84**	0.66*	0.88**	0.82**	0.45	0.27	0.54	0.57	0.29	0.44
Tester/*gca*	0.44	0.61*	0.53	0.65*	0.75**	0.39	0.38	0.76**	0.47	-0.13	0.84**	0.88**	0.83**	0.53
Cross/*sca*	0.63*	0.66*	0.50	0.50	0.63*	0.64*	0.55	0.52	0.78**	0.60*	0.65*	0.73**	0.78**	0.84**

*,** F probability significant at P 0.05 and 0.01, respectively

3.1.4. Crosses Performance *Per Se* and Specific Combining Ability Effects

Per se performance of hybrids and their *sca* effects were presented in the Table 6. Based on the mean performance of hybrids across two environments, the number of days to 50% flowering varied from 45.00 (ICMX 187861) to 64.00 days (ICMX 1871018) at Sadore and Gampela. Twenty-four hybrids showed earlier flowering than the overall means and among them, the hybrids ICMX 1871008, ICMX 187762 and ICMX 187849 had significant and negative *sca* effects across the locations, whereas in addition to these few other hybrids had exhibited significant and negative *sca* effects for days to 50% flowering at single locations.

The plant height means varied from 124.00 (ICMX 1871005) to 254.00 cm (ICMX 1871002) at Sadore and from 108.50 (ICMX 1871005) to 254.50 cm (ICMX 187885) at Gampela (Table 6). ICMX 187849 (51.63**, 31.11** at Sadore and Gampela, respectively) and ICMX 187850 (28.63**, 52.00**) showed highly significant and positive *sca* effects across locations; whereas, ICMH 177016, ICMH 177111, ICMX 187002, ICMX 187865, ICMX 1871017, ICMX 187875, ICMX 1871035, ICMX 187807, and ICMX 187853 at Sadore, ICMX 187876, ICMX 187885, ICMX 187897, ICMH 177018, ICMX 1871023, ICMX 187762, and ICMX 187812 at Gampela exhibited positive and significant *sca* effects. The hybrids ICMX 187849, ICMX 187850 had plant height greater than the overall means with positive and significative *sca* effects at both Sadore and Gampela.

The panicle length means were ranged from 24.50 (ICMX 187848) to 47.50 cm (ICMH IS 16008 and ICMH IS 16012) at Sadore and from 26.00 (ICMX 187861) to 53.00 cm (ICMX 177017) at Gampela (Table 6). ICMH 177016, ICMH IS 16012 and ICMH 177002 had significant and positive *sca* effects with means greater than the overall means for panicle length across locations and 13 hybrids at Sadore and 5 at Gampela had exhibited significant and positive *sca* effects. The hybrids ICMX 187893 and ICMX 187895 had significant and positive *sca* effects for panicle circumference in the two environments with means ranging from 7.00 (ICMX 1871018, ICMX 1871019 and ICMX 187875) to 11.00 cm (ICMX 187856, ICMX 187848 and ICMX 187829) at Sadore and from 6.00 (ICMX 1871020) to 12.00 cm (ICMX 187829) at Gampela. ICMX 187876 (0.94*), ICMX 1871030 (1.49**), and ICMX 187813 (1.19*) showed significant and positive *sca* effects in Gampela.

Grain yield varied from 0.60 (ICMX 187763) to 3.06 t/ha (ICMX 1871038) at Sadore and from 0.43 (ICMX 187880) to 3.45 t/ha (ICMX 1871038) at Gampela (Table 6). ICMH 177016, ICMX 187892, ICMX 187895, ICMX 1871013 ICMX 1871014, ICMX 1871038, ICMH 147008, ICMX 187872, ICMX 187769, ICMX 187765, ICMX 1871029, ICMX

1871033, ICMX 1871034, ICMX 187825, ICMX 187827, ICMX 187830 and ICMX 187851 had exhibited significant and positive *sca* effects for grain yield across locations. All these 17 hybrids had also mean greater than the overall means. Fifteen hybrids in each location showed significant and positive *sca* effects for grain yield.

The grain Fe and Zn contents varied from 27.58 (ICMX 1871038) to 53.78 mgkg^{-1}(ICMX 187897) and 33.50 (ICMX 1871004) to 66.00 mgkg^{-1} (ICMX 187897) for Fe; 23.33 (ICMX 1871038) to 44.23 mgkg^{-1} (ICMX 187868) and 31.40 (ICMX 187813) to 50.90 mgkg^{-1} (ICMX 187885) for Zn at Sadore and Gampela, respectively (Table 6). ICMH 177016, ICMX 187892, CMX 187861, ICMX 187803 and ICMX 187851 for grain Fe and ICMH 177016 and ICMX 1871002 hybrids for grain Zn contents had significant and positive *sca* effects with means greater than the overall means across locations. Eleven hybrids at sadore and 22 hybrids at Gampela showed significant and positive *sca* effects.

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMH 177016	56.50	1.29	58.50	2.57	238.00	29.37**	190.50	-9.23	42.50	4.93*	47.50	5.78*	9.00	-0.01	9.50	0.33
ICMX 187876	49.00	-2.10	58.00	3.45*	218.00	8.76	233.50	28.66**	31.50	-4.07*	34.50	0.17	9.50	0.26	11.00	0.94*
ICMX 187877	61.00	5.84**	57.50	1.23	211.50	-0.57	208.50	-2.39	31.50	-3.51*	33.00	-1.39	9.50	-0.13	11.00	0.56
ICMX 187878	49.00	-0.60	52.00	0.73	220.50	13.70	179.50	-18.17	34.50	-4.85**	35.50	-3.50	7.50	-0.63	7.50	-0.61
ICMX 187880	47.50	-1.82	55.00	1.40	220.50	8.04	196.00	-0.06	39.50	1.15	40.00	1.94	8.50	0.26	8.00	-1.06*
ICMX 187882	49.50	2.79	52.50	3.23*	177.00	-34.19**	194.00	4.22	32.00	-1.24	36.00	3.00	8.50	-0.51	9.00	-0.22
ICMH IS 16008	49.00	-1.66	48.50	-4.10*	230.50	-3.63	228.00	7.16	47.50	5.60**	40.00	-3.06	9.00	0.10	10.50	0.89
ICMH IS 16009	49.00	-1.66	51.50	-1.38	237.50	15.04	237.50	17.16	34.50	-1.51	32.50	-4.56	7.50	-0.24	8.50	-0.39
ICMX 187989	51.00	-1.38	48.50	-4.71**	151.50	-5.02	149.00	-9.73	43.00	1.21	37.50	-1.06	8.00	0.21	8.00	0.00
ICMX 187990	51.50	-0.05	54.50	0.34	135.00	-26.74**	124.00	-30.89**	39.50	0.99	35.50	-3.50	8.50	0.93	8.00	-0.44
ICMX 187991	51.50	2.07	53.00	0.90	144.50	-10.24	143.50	-4.01	40.00	1.88	44.50	6.17*	7.50	-0.29	8.50	0.39
ICMX 187992	47.50	-2.71	50.00	-3.66*	170.00	5.48	169.50	17.27	41.00	-0.57	41.50	0.00	8.00	0.04	7.50	-0.39
ICMH 177017	54.50	-6.13**	61.00	1.77	228.00	13.66	237.50	22.52*	38.00	-1.57	53.00	8.99**	10.00	0.78	8.50	-0.71
ICMX 187883	56.50	-0.02	57.50	-0.34	225.00	10.05	207.50	-12.59	36.50	-1.07	35.50	-1.13	9.50	0.06	10.50	0.40
ICMX 187885	58.00	-2.57	58.50	-1.06	225.00	7.22	254.50	28.36**	34.00	-3.01	32.00	-4.68	8.50	-1.33*	10.50	0.01

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMH 177111	59.00	3.98*	58.00	3.44	244.00	31.50**	208.50	-4.42	43.00	1.65	39.00	-2.29	8.50	0.17	8.00	-0.15
ICMH 177022	56.50	1.76	58.00	1.11	223.00	4.83	226.50	15.19	39.00	-1.35	41.50	1.15	8.50	0.06	9.00	-0.10
ICMX 187766	46.50	-5.63**	50.50	-2.06	227.50	10.61	202.00	-3.03	36.50	1.26	31.00	-4.29	9.00	-0.22	9.00	-0.26
ICMH IS 16012	56.00	-0.07	59.00	3.11	246.50	6.66	253.00	16.91	47.50	3.60*	52.00	6.65*	10.00	0.89	10.50	0.85
ICMH IS 16013	58.50	2.43	56.50	0.33	208.50	-19.67*	214.00	-21.59*	34.50	-3.51*	39.00	-0.35	8.00	0.06	8.50	-0.43
ICMX 187995	58.50	0.70	56.50	-0.01	140.50	-21.73*	170.50	-3.48	45.00	1.21	43.00	2.15	7.50	-0.50	8.00	-0.04
ICMX 187996	60.00	3.04*	56.50	-0.95	156.00	-11.45	164.00	-6.14	43.50	2.99	41.50	0.21	8.50	0.72	8.00	-0.49
ICMX 187997	55.50	0.65	53.00	-2.39	148.00	-12.45	147.50	-15.26	44.00	3.88*	35.50	-5.13*	8.00	0.00	8.50	0.35
ICMX 187998	57.50	1.87	54.00	-2.95	151.00	-19.23*	151.00	-16.48	39.50	-4.07*	42.50	-1.29	7.50	-0.67	8.50	0.57
ICMH 177020	55.50	-1.30	57.00	0.73	207.50	8.20	181.50	-3.81	39.50	1.43	43.00	1.44	9.50	-0.22	9.00	-0.08
ICMX 187891	55.50	2.82	55.50	0.62	182.50	-17.41	193.00	2.58	37.00	0.93	31.50	-2.67	10.50	0.56	10.50	0.53
ICMX 187892	58.00	1.26	57.50	0.90	198.50	-4.24	190.00	-6.48	33.50	-2.01	33.00	-1.22	10.50	0.17	9.50	-0.86
ICMX 187893	54.00	2.82	50.00	-1.60	199.00	1.54	196.50	13.25	38.00	-1.85	37.00	-1.83	10.00	1.17*	9.00	0.97*
ICMX 187895	48.00	-2.91	54.50	0.57	217.50	14.37	189.00	7.36	41.00	2.15	39.50	1.61	10.00	1.06*	10.00	1.03*
ICMX 187897	49.50	1.20	48.50	-1.10	207.50	5.65	205.00	29.63**	34.50	0.76	34.00	1.17	10.50	0.78	10.00	0.86

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMX 1871001	48.50	-3.74	56.50	3.57*	228.00	3.20	201.50	-4.92	46.00	3.60*	44.50	1.61	8.50	-1.11*	8.50	-1.03*
ICMX 1871002	50.50	-1.74	56.50	3.29*	254.00	40.87*	197.00	-8.92	34.50	-2.01	40.00	3.11	8.00	-0.44	7.50	-1.31*
ICMX 1871003	51.50	-2.46	53.00	-0.55	136.50	-10.69	141.00	-3.31	36.00	-6.29**	35.00	-3.39	8.50	0.00	8.00	0.08
ICMX 1871004	53.50	0.37	54.50	0.01	155.00	2.59	148.00	7.52	38.00	-1.01	36.00	-2.83	7.50	-0.78	8.50	0.14
ICMX 1871005	53.50	2.48	52.00	-0.44	124.00	-21.41*	108.50	-24.59*	43.00	4.38*	41.50	3.33	8.00	-0.50	8.00	-0.03
ICMX 1871006	53.00	1.20	48.00	-5.99**	132.50	-22.69*	129.50	-8.31	42.00	-0.07	41.00	-0.33	8.00	-0.67	7.50	-0.31
ICMH 177023	61.50	6.33**	60.00	5.23**	185.00	-0.55	184.00	4.69	33.00	-1.86	37.50	-0.22	9.50	0.03	9.50	-0.08
ICMX 187854	53.50	2.44	54.00	0.62	192.00	5.84	188.50	4.08	31.50	-1.36	32.00	1.67	10.00	0.31	10.00	-0.47
ICMX 187856	55.50	0.38	54.00	-1.10	203.00	14.01	173.00	-17.48	33.00	0.69	30.00	-0.39	11.00	0.92	11.00	0.14
ICMX 187857	48.50	-1.06	48.00	-2.10	148.50	-35.21**	157.50	-19.76*	34.50	-2.14	34.00	-1.00	8.00	-0.58	8.50	-0.03
ICMX 187859	48.50	-0.78	50.50	-1.94	192.50	3.12	168.00	-7.64	33.50	-2.14	37.50	3.44	8.00	-0.69	10.00	0.53
ICMX 187861	44.50	-2.17	46.50	-1.60	182.50	-5.60	173.00	3.63	30.00	-0.53	26.00	-3.00	10.00	0.53	10.00	0.36
ICMX 1871013	52.50	1.88	51.00	-0.44	216.00	4.95	204.00	3.58	37.00	-2.19	34.00	-5.06*	9.00	-0.36	10.50	0.47
ICMX 1871014	53.00	2.38	48.50	-3.21*	202.50	3.12	214.50	14.58	36.50	3.19	34.50	1.44	8.00	-0.19	8.00	-1.31*
ICMH 177002	51.50	-0.84	51.00	-1.05	139.00	5.57	139.00	0.69	46.50	7.42**	40.00	5.44*	9.00	0.75	8.50	0.08

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMX 1871008	48.50	-3.01*	49.50	-3.49*	140.50	1.84	141.50	7.02	36.50	0.69	34.50	-0.50	7.50	-0.53	9.00	0.14
ICMX 1871009	47.00	-2.39	54.50	3.57*	130.00	-1.66	132.00	4.91	29.50	-5.92**	34.00	-0.33	8.00	-0.25	9.00	0.47
ICMX 1871010	47.00	-3.17*	58.00	5.51**	146.00	4.57	133.50	1.69	43.00	4.14*	36.00	-1.50	8.50	0.08	8.00	-0.31
ICMX 1871038	60.00	0.87	55.00	-3.60	194.50	-4.38	199.50	5.73	39.00	2.14	40.00	-0.97	8.50	-0.31	8.50	-0.13
ICMX 187862	55.50	0.48	58.00	0.79	191.50	-7.99	192.50	-6.38	34.00	-0.86	35.50	1.92	9.00	-0.03	10.00	0.49
ICMX 187864	62.00	2.93	64.50	5.57**	214.00	11.68	216.00	11.07	35.00	0.69	35.50	1.86	9.50	0.08	9.50	-0.40
ICMX 187865	49.00	-4.52**	53.50	-0.44	217.50	20.45*	199.50	7.79	39.50	0.86	37.00	-1.25	7.50	-0.42	7.00	-0.57
ICMX 187867	52.50	-0.74	53.50	-2.77	191.00	-11.71	216.00	25.90*	36.00	-1.64	35.50	-1.81	8.00	-0.03	9.00	0.49
ICMX 187868	47.00	-3.63*	52.00	0.07	205.00	3.57	164.50	-19.32*	32.50	-0.03	33.50	1.25	9.50	0.69	9.50	0.82
ICMH 147008	56.50	1.93	53.00	-2.27	233.00	8.62	231.00	16.12	43.50	2.31	47.00	4.69	9.00	0.31	9.00	-0.07
ICMX 1871017	50.00	-4.57**	53.50	-2.05	236.00	23.29*	236.50	22.12	38.50	3.19	38.50	2.19	8.00	0.47	8.50	0.15
ICMX 1871018	63.50	7.20**	57.00	1.12	127.50	-19.27*	126.50	-26.27*	34.50	-6.58**	34.00	-3.81	7.00	-0.58	7.50	0.04
ICMX 1871019	60.50	5.04**	58.00	1.18	145.00	-6.99	138.50	-10.44	36.50	-1.31	41.00	2.75	7.00	-0.36	8.50	0.60
ICMX 1871020	48.50	-4.85**	56.00	1.23	142.50	-2.49	122.00	-19.55*	38.50	1.08	34.50	-3.08	7.50	-0.08	6.00	-1.57**
ICMX 1871021	54.00	-0.13	57.50	1.18	140.00	-14.77	139.50	-6.77	41.00	0.14	37.00	-3.75	8.00	0.25	7.50	0.15

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMH 177018	61.00	1.12	57.00	0.11	197.50	-6.09	220.00	29.07**	36.00	-0.15	44.00	1.32	9.00	-0.22	9.00	0.21
ICMX 187870	54.50	-1.27	53.00	-2.51	215.50	11.30	212.50	16.45	35.00	0.85	32.50	-2.79	9.50	0.06	10.50	0.82
ICMX 187872	56.00	-3.82*	56.00	-1.23	218.50	11.47	185.00	-17.10	36.50	2.90	38.50	3.15	9.50	-0.33	10.00	-0.07
ICMX 1871046	55.00	0.73	51.50	-0.73	150.00	-51.76**	179.00	-9.88	38.00	0.07	43.50	3.54	8.00	-0.33	8.00	0.26
ICMX 187875	53.00	-0.99	53.50	-1.06	230.00	22.58*	162.00	-25.27*	43.50	6.57**	43.00	3.99	7.00	-1.44**	8.00	-0.68
ICMX 187769	55.00	3.62*	49.50	-0.73	219.50	13.36	157.50	-23.49*	27.50	-4.32*	31.50	-2.46	9.00	-0.22	8.00	-0.85
ICMH 147010	57.50	2.18	54.00	0.44	242.50	13.41	213.50	1.45	34.50	-5.99**	39.00	-5.01*	10.00	0.89	9.50	0.26
ICMH 147009	55.00	-0.32	56.00	2.16	194.50	-22.92*	206.00	-5.55	36.50	1.90	37.50	-0.51	8.50	0.56	9.00	0.49
ICMX 1871023	56.00	-1.05	57.00	2.83	142.50	-8.98	171.50	21.57*	46.00	5.63**	37.00	-2.51	8.50	0.50	7.50	-0.13
ICMX 1871024	55.50	-0.71	55.50	0.38	140.50	-16.20	135.00	-11.10	33.00	-4.10*	42.50	2.54	8.00	0.22	7.50	-0.57
ICMX 1871025	55.00	0.90	54.00	0.94	167.50	17.80	157.50	18.79	39.50	2.79	44.00	4.71	7.50	-0.50	7.50	-0.24
ICMX 1871029	54.50	-0.38	54.00	-0.62	175.50	16.02	148.50	5.07	34.00	-6.15**	36.50	-5.96*	9.00	0.83	8.00	0.49
ICMH 177019	52.50	-0.38	50.00	-2.60	185.00	-4.80	154.00	-19.35*	32.00	-1.40	33.00	-4.72	9.50	0.03	10.00	0.71
ICMX 187068	47.00	-1.77	49.00	-2.21	187.00	-3.41	150.50	-27.96**	31.50	0.10	31.00	0.67	9.00	-0.69	8.50	-1.68**
ICMX 187762	47.50	-5.32**	49.00	-3.94*	202.00	8.76	210.00	25.48*	34.00	3.15	31.50	1.11	10.50	0.42	11.00	0.43

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMX 1871027	49.50	2.23	47.50	-0.44	182.50	-5.46	188.50	17.20	35.50	0.32	37.00	2.00	9.50	0.92	8.00	-0.24
ICMX 187763	48.00	1.01	55.00	4.73**	182.50	-11.13	167.50	-2.19	26.50	-7.68**	31.00	-3.06	9.50	0.81	9.00	-0.18
ICMX 187765	49.00	4.62**	47.50	1.57	190.50	-1.85	165.00	1.59	29.50	0.43	29.00	0.00	9.50	0.03	9.50	0.15
ICMX 1871029	45.50	-2.82	47.50	-1.77	211.00	-4.30	170.50	-23.96*	35.50	-2.24	44.00	4.94	9.50	0.14	8.50	-1.24*
ICMX 1871030	48.50	0.18	46.50	-3.05	180.00	-23.63*	202.00	8.04	36.00	4.15*	36.00	2.94	7.50	-0.69	10.50	1.49*
ICMX 1871032	51.50	1.45	51.00	1.12	145.50	7.82	127.50	-4.85	37.00	-0.63	33.00	-1.56	8.00	-0.25	8.00	-0.13
ICMX 1871033	47.00	-2.21	55.50	4.68**	143.50	0.59	145.00	16.48	33.50	-0.85	31.50	-3.50	7.50	-0.53	9.50	0.93
ICMX 1871034	49.00	1.90	48.00	-0.77	142.50	6.59	131.50	10.37	35.00	1.04	33.00	-1.33	8.50	0.25	8.50	0.26
ICMX 1871035	49.00	1.12	53.00	2.68	176.50	30.82**	125.00	-0.85	41.00	3.60*	40.00	2.50	8.00	-0.42	7.50	-0.51
ICMX 187825	53.00	-2.96	53.00	-2.27	209.00	2.33	203.00	10.61	41.00	2.10	35.00	-9.18**	8.50	-0.60	9.50	0.42
ICMX 187803	51.50	-0.35	55.00	1.12	206.00	-1.28	211.00	13.50	42.50	5.60**	39.50	2.71	9.00	-0.32	9.00	-0.97*
ICMX 187806	58.00	2.09	57.00	1.40	206.50	-3.62	204.50	0.94	38.00	1.65	39.50	2.65	10.00	0.29	10.50	0.14
ICMX 187807	47.50	-2.85	48.50	-2.10	224.00	19.16*	189.50	-0.84	44.50	3.82*	42.50	1.04	7.50	-0.71	8.50	0.47
ICMX 187808	53.00	2.93	52.00	-0.94	196.50	-14.01	162.50	-26.23*	39.00	-0.68	35.50	-5.01*	8.00	-0.32	8.50	-0.47
ICMX 187786	48.50	1.04	50.00	1.40	225.00	15.77	173.50	-8.95	34.50	-0.07	36.50	1.04	8.50	-0.60	8.00	-1.14*

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMX 187812	56.00	4.59**	52.50	0.57	228.00	-4.17	241.50	28.00**	42.50	-0.74	47.50	1.99	9.00	0.01	9.00	-0.53
ICMX 187813	50.00	-1.41	54.00	1.79	217.00	-3.51	214.00	1.00	32.00	-5.35**	37.00	-2.51	8.50	0.68	10.00	1.19*
ICMX 187826	51.00	-2.13	51.00	-1.55	161.00	6.44	165.00	13.61	43.50	0.38	40.00	-1.01	8.50	0.63	8.50	0.58
ICMX 187822	54.00	1.70	54.50	1.01	164.50	4.72	144.00	-3.56	40.00	0.15	48.50	7.04*	7.50	-0.15	8.00	-0.36
ICMX 187823	49.50	-0.69	51.00	-0.44	148.00	-4.78	117.50	-22.67*	30.50	-8.96**	36.00	-4.79	8.50	0.63	8.50	0.47
ICMX 187824	49.00	-1.96	53.00	0.01	145.50	-17.06	139.50	-5.39	45.00	2.10	50.00	6.04*	8.50	0.46	8.00	0.19
ICMX 187848	58.50	1.16	53.00	-1.94	193.50	-37.76**	181.00	-40.23**	24.50	-5.61**	33.50	-2.43	11.00	0.53	10.00	-0.67
ICMX 187827	53.00	-0.23	52.00	-1.55	226.00	-5.87	208.00	-18.34	28.00	-0.11	28.00	-0.54	10.50	-0.19	11.50	-0.06
ICMX 187829	56.50	-0.78	53.50	-1.77	190.00	-44.70**	210.00	-22.39*	27.00	-0.56	27.50	-1.10	11.00	-0.08	12.00	0.06
ICMX 187830	51.00	-0.73	53.50	3.23*	235.50	6.08	234.00	14.83	34.00	2.11	36.50	3.29	10.00	0.42	9.50	-0.11
ICMX 187832	53.00	1.55	51.50	-1.10	219.00	-16.09	230.50	12.94	34.50	3.61*	30.00	-2.26	10.00	0.31	11.00	0.44
ICMX 187788	47.00	-1.84	47.50	-0.77	226.50	-7.31	227.00	15.72	29.50	3.72*	30.50	3.29	10.00	-0.47	11.00	0.28
ICMX 187836	50.50	-2.28	52.50	0.90	232.00	-24.76*	198.00	-44.34**	30.50	-3.94*	30.50	-6.76*	9.50	-0.86	11.50	0.39
ICMX 187790	57.50	4.72**	54.00	2.12	232.50	-12.59	215.00	-26.84*	28.50	-0.06	29.50	-1.76	9.00	-0.19	10.50	0.11
ICMX 187853	53.00	-1.51	55.00	2.79	225.00	45.86**	192.00	11.77	32.00	-2.33	38.50	5.74*	8.50	-0.75	9.00	-0.50

Table 6. Performance *per se* of crosses and their specific combining ability (*sca*) effects of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMX 187849	49.50	-4.17*	50.00	-3.16*	236.00	51.63**	207.50	31.11**	33.50	2.44	31.00	-2.21	9.50	0.47	10.00	0.06
ICMX 187850	51.50	-0.06	48.50	-2.60	206.00	28.63**	221.00	52.00**	30.50	-0.17	33.00	0.46	10.00	0.75	9.50	-0.11
ICMX 187851	56.50	4.16**	56.50	3.84*	204.00	16.86	187.50	13.77	35.00	0.89	40.00	4.29	9.50	0.08	9.50	0.11

*,** F probability significant at P 0.05 and 0.01, respectively

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	Grain yield				Grain Fe content				Grain Zn content			
Locations	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
Crosses	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMH 177016	1.86	0.23*	2.93	0.89**	46.65	7.25**	50.73	5.25**	40.90	8.00**	50.38	9.75**
ICMX 187876	2.00	0.16	2.19	0.55**	44.40	-1.06	47.25	-2.95*	33.08	-3.99*	35.50	-8.44**
ICMX 187877	1.41	-0.35*	2.64	-0.02	40.83	-3.68*	47.70	1.70	33.43	-0.24	42.35	-1.03
ICMX 187878	1.67	-0.02	1.67	0.33**	46.05	1.59	46.23	0.96	37.03	1.90	47.15	3.37*
ICMX 187880	1.46	-0.05	0.43	-0.65**	36.68	-1.54	42.60	-1.10	29.38	-3.57*	40.33	0.10
ICMX 187882	1.27	-0.21	1.53	0.12	42.63	-6.10**	45.50	-9.11**	38.38	-1.46	39.15	-5.28**
ICMH IS 16008	1.64	-0.25*	1.35	-0.41**	42.50	1.41	46.58	1.31	35.55	1.10	45.65	5.30**
ICMH IS 16009	2.05	0.14	1.50	-0.12	39.00	0.38	40.50	-1.33	33.70	0.08	37.00	-1.75
ICMX 187989	1.26	-0.14	1.14	0.00	36.58	-1.41	44.75	0.56	31.58	-1.60	40.50	0.21
ICMX 187990	2.09	0.62**	0.74	-0.49**	35.43	-3.38*	41.50	-1.74	31.50	-2.09	37.50	-2.09
ICMX 187991	1.14	-0.17	0.99	-0.09	43.30	2.77	52.10	6.69**	31.80	-2.29	46.25	4.14*
ICMX 187992	1.47	0.02	0.95	-0.10	42.93	3.77*	44.50	-0.24	37.50	4.14**	35.50	-4.29*
ICMH 177017	2.03	-0.27*	2.17	-0.07	43.30	5.08**	46.50	1.11	32.13	0.81	33.00	-7.82**
ICMX 187883	2.86	0.35**	1.95	0.11	49.55	5.27**	52.83	2.72	34.55	-0.92	49.98	5.84**
ICMX 187885	2.75	0.33**	3.01	0.15	44.33	0.99	52.98	7.06**	33.50	1.42	50.90	7.33**

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	**Grain yield**				**Grain Fe content**				**Grain Zn content**			
Locations	**Sadore**		**Gampela**		**Sadore**		**Gampela**		**Sadore**		**Gampela**	
Crosses	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**
ICMH 177111	2.63	0.28*	1.45	-0.09	44.70	1.42	41.75	-3.42*	35.20	1.67	47.68	3.69*
ICMH 177022	2.04	-0.13	1.70	0.42**	36.50	-0.53	46.73	3.11*	32.50	1.14	43.10	2.68
ICMX 187766	2.20	0.06	1.38	-0.23*	45.48	-2.08	55.00	0.48	38.93	0.68	46.30	1.67
ICMH IS 16012	2.08	-0.48**	1.68	-0.28**	38.48	-1.44	46.25	1.08	32.50	-0.36	40.23	-0.32
ICMH IS 16013	2.80	0.23*	1.52	-0.29**	36.43	-1.02	36.63	-5.11**	30.00	-2.03	32.90	-6.04**
ICMX 187995	2.36	0.30*	1.44	0.11	34.13	-2.68	44.55	0.46	30.00	-1.59	41.00	0.52
ICMX 187996	1.64	-0.49**	1.26	-0.17	40.58	2.94	43.90	0.75	32.13	0.12	40.13	0.34
ICMX 187997	1.91	-0.07	1.71	0.43**	33.85	-5.50**	36.98	-8.35**	31.50	-1.00	33.90	-8.41**
ICMX 187998	1.99	-0.13	1.15	-0.10	35.53	-2.45	44.75	0.10	31.83	0.06	40.50	0.52
ICMH 177020	1.73	-0.30*	1.43	-0.65**	43.88	2.15	49.00	2.69	33.10	-0.81	39.50	0.45
ICMX 187891	2.16	-0.07	1.53	-0.15	42.50	-5.28**	43.00	-8.04**	34.18	-3.90*	33.50	-8.87**
ICMX 187892	2.53	0.38**	2.88	0.18*	51.60	4.77**	51.33	4.48**	32.50	-2.18	48.75	6.94**
ICMX 187893	1.53	-0.54**	0.96	-0.41**	49.65	2.87	42.50	-3.60*	34.78	-1.36	35.50	-6.72**
ICMX 187895	3.03	1.14**	1.31	0.19*	45.20	4.66**	47.00	2.46	42.98	9.02**	41.30	2.64
ICMX 187897	1.96	0.09	2.19	0.74**	53.78	2.72	66.00	10.56**	42.50	1.66	44.00	1.14

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	Grain yield				Grain Fe content				Grain Zn content			
Locations	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
Crosses	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
ICMX 1871001	2.49	0.21*	1.40	-0.40**	43.33	-0.09	43.00	-3.10*	37.58	2.12	35.50	-3.28*
ICMX 1871002	2.11	-0.19	1.78	0.12	41.65	0.70	44.68	2.01	39.68	5.05**	42.73	5.55**
ICMX 1871003	1.92	0.14	1.56	0.39**	35.10	-5.21**	46.13	1.10	32.50	-1.69	42.20	3.48*
ICMX 1871004	1.52	-0.34**	1.14	-0.13	32.20	-8.93**	33.50	-10.58**	30.80	-3.80*	31.50	-6.52**
ICMX 1871005	1.54	-0.16	1.10	-0.01	40.95	-1.91	51.35	5.10**	31.28	-3.82*	48.45	7.91**
ICMX 1871006	1.49	-0.35**	1.21	0.13	45.03	3.54*	42.50	-3.08*	34.08	-0.29	35.50	-2.72
ICMH 177023	1.47	-0.35**	1.98	-0.05	33.43	-3.85*	44.83	-1.97	30.53	0.40	43.90	1.77
ICMX 187854	1.88	-0.15	2.35	0.71**	36.48	-6.85**	54.20	2.68	29.75	-4.53**	47.58	2.12
ICMX 187856	2.10	0.15	3.28	0.62**	47.15	4.77**	39.98	-7.35**	33.23	2.34	36.90	-7.99**
ICMX 187857	2.06	0.18	1.26	-0.07	43.35	1.02	44.40	-2.18	31.95	-0.40	43.20	-2.10
ICMX 187859	1.53	-0.16	0.57	-0.52**	35.90	-0.18	42.70	-2.32	31.48	1.31	39.40	-2.34
ICMX 187861	1.91	0.24*	1.16	-0.26**	50.80	4.20*	63.55	7.62**	33.60	-3.46*	43.85	-2.10
ICMX 1871013	2.31	0.23*	1.97	0.22*	41.50	2.54	48.23	1.65	31.50	-0.17	42.98	1.11
ICMX 1871014	2.48	0.38**	1.90	0.28**	38.65	2.16	42.05	-1.10	32.15	1.31	40.68	0.42
ICMH 177002	1.20	-0.39**	0.90	-0.24*	33.25	-2.61	44.70	-0.80	31.70	1.30	38.63	-3.18*

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	**Grain yield**				**Grain Fe content**				**Grain Zn content**			
Locations	**Sadore**		**Gampela**		**Sadore**		**Gampela**		**Sadore**		**Gampela**	
Crosses	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**
ICMX 1871008	1.71	0.05	1.15	-0.07	35.78	-0.91	45.43	0.87	31.60	0.79	45.70	4.60**
ICMX 1871009	0.93	-0.57**	0.79	-0.28**	40.50	2.10	50.18	3.44*	32.50	1.19	48.25	4.62**
ICMX 1871010	2.03	0.38**	0.71	-0.34**	34.65	-2.38	45.53	-0.54	30.50	-0.08	44.35	3.05
ICMX 1871038	3.06	0.97**	3.45	1.15**	27.58	-7.22**	36.98	-7.08**	23.33	-7.59**	36.35	-2.39
ICMX 187862	2.04	-0.27*	1.41	-0.50**	41.85	0.99	42.60	-6.18**	37.58	2.50	36.63	-5.44**
ICMX 187864	2.07	-0.16	2.81	-0.12	35.93	-3.98*	44.80	0.22	32.50	0.82	42.10	0.60
ICMX 187865	2.28	0.13	1.28	-0.32**	39.73	-0.13	47.88	4.03*	32.35	-0.79	44.13	2.22
ICMX 187867	2.40	0.43**	1.24	-0.11	30.18	-3.44*	42.55	0.27	25.30	-5.66**	38.45	0.10
ICMX 187868	1.56	-0.39**	1.52	-0.17	51.50	7.37**	52.70	-0.49	44.23	6.37**	42.55	-0.01
ICMH 147008	2.61	0.26*	2.30	0.28**	34.48	-2.01	44.73	0.89	30.75	-1.72	40.35	1.88
ICMX 1871017	2.27	-0.11	2.06	0.17	34.00	-0.02	47.48	7.07**	30.50	-1.14	41.75	4.88**
ICMX 1871018	1.30	-0.56**	1.53	0.12	35.00	1.61	42.25	-0.51	30.50	-0.69	37.50	-0.91
ICMX 1871019	1.72	-0.22*	1.26	-0.23*	32.50	-1.71	46.65	4.83**	30.50	-1.11	38.75	1.04
ICMX 1871020	1.86	0.09	0.89	-0.45**	43.03	7.09**	45.35	1.36	38.20	6.09**	41.63	1.39
ICMX 1871021	1.73	-0.19	1.50	0.18*	36.00	1.44	38.90	-4.42**	34.30	2.93*	34.55	-3.36*

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	Grain yield				Grain Fe content				Grain Zn content			
Locations	**Sadore**		**Gampela**		**Sadore**		**Gampela**		**Sadore**		**Gampela**	
Crosses	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**
ICMH 177018	1.92	-0.01	1.72	-0.42**	31.60	-4.79**	48.20	3.21*	27.73	-3.06*	44.00	4.04*
ICMX 187870	1.85	-0.29*	1.77	0.02	48.30	5.86**	52.48	2.77	43.43	8.48**	44.45	1.17
ICMX 187872	2.43	0.36**	3.39	0.63**	36.20	-5.30**	40.80	-4.72**	23.78	-7.78**	36.93	-5.79**
ICMX 1871046	1.41	-0.58**	1.12	-0.32**	39.23	-2.22	46.23	1.45	35.35	2.34	39.95	-3.18*
ICMX 187875	1.96	0.15	1.32	0.13	35.55	0.35	42.83	-0.39	27.93	-2.90*	39.80	0.24
ICMX 187769	2.41	0.63**	1.71	0.19*	44.25	-1.47	56.00	1.88	34.93	-2.79	49.78	6.00**
ICMH 147010	2.09	-0.10	1.52	-0.34**	42.60	4.52**	45.93	1.15	34.13	1.79	42.65	2.96
ICMH 147009	2.10	-0.12	1.34	-0.38**	36.30	0.69	42.08	0.74	28.45	-3.05*	39.85	1.76
ICMX 1871023	1.47	-0.23*	1.29	0.05	35.83	0.85	43.53	-0.17	31.45	0.39	39.93	0.30
ICMX 1871024	1.98	0.21	1.49	0.16	41.85	6.05**	41.00	-1.75	35.15	3.68*	36.50	-2.43
ICMX 1871025	2.06	0.44**	1.17	-0.01	32.88	-4.65**	42.50	-2.42	31.65	-0.32	36.50	-4.95**
ICMX 1871029	1.29	-0.47**	1.44	0.29**	36.25	0.11	42.50	-1.75	34.45	3.21*	39.00	-0.13
ICMH 177019	1.32	-0.29*	1.58	-0.20*	45.88	6.29**	46.70	2.07	33.33	2.13	35.50	-2.02
ICMX 187068	1.39	-0.44**	0.78	-0.60**	45.90	0.25	50.50	1.14	35.50	0.15	40.00	-0.84
ICMX 187762	1.39	-0.36**	1.64	-0.76**	43.90	-0.80	44.50	-0.66	33.38	1.42	41.70	1.42

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	**Grain yield**				**Grain Fe content**				**Grain Zn content**			
Locations	**Sadore**		**Gampela**		**Sadore**		**Gampela**		**Sadore**		**Gampela**	
Crosses	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**
ICMX 1871027	1.10	-0.57**	0.82	-0.26**	42.10	-2.55	49.30	4.88**	31.58	-1.84	46.85	6.16**
ICMX 187763	0.60	-0.89**	0.77	-0.06	40.58	2.17	43.00	0.14	32.50	1.26	33.00	-4.13*
ICMX 187765	2.65	1.19**	1.54	0.39**	46.50	-2.42	53.25	-0.51	36.83	-1.30	44.80	3.47*
ICMX 1871029	2.12	0.25*	1.76	0.26**	41.93	0.64	44.20	-0.22	34.13	1.38	33.50	-3.75*
ICMX 1871030	1.75	-0.14	1.68	0.32**	36.48	-2.34	40.53	-0.46	31.50	-0.41	33.60	-2.05
ICMX 1871032	1.68	0.30*	0.94	0.06	39.53	1.35	42.88	-0.47	32.45	0.98	38.48	1.29
ICMX 1871033	1.78	0.33**	1.57	0.60**	42.95	3.95*	40.50	-1.90	31.03	-0.86	32.50	-3.99*
ICMX 1871034	1.75	0.46**	1.18	0.36**	39.70	-1.02	40.98	-3.60*	34.30	1.92	40.65	1.64
ICMX 1871035	1.59	0.16	0.68	-0.10	33.83	-5.52**	43.48	-0.43	26.83	-4.82**	39.50	2.81
ICMX 187825	2.42	0.34**	2.80	0.66**	31.50	-3.14*	36.50	-6.05**	30.50	0.11	32.50	-4.46**
ICMX 187803	2.58	0.28*	1.07	-0.68**	43.83	3.13*	54.95	7.68**	36.80	2.25	50.80	10.52**
ICMX 187806	2.22	0.00	2.16	-0.60**	38.98	-0.77	45.45	2.37	31.50	0.34	43.13	3.41*
ICMX 187807	2.54	0.40**	1.40	-0.04	40.35	0.65	43.80	1.46	32.25	-0.36	40.75	0.63
ICMX 187808	1.50	-0.46**	1.20	0.01	32.00	-1.45	42.00	1.23	30.50	0.06	39.10	2.54
ICMX 187786	1.39	-0.55**	1.24	-0.29**	41.73	-2.24	40.93	-10.76**	40.48	3.15*	36.88	-3.90*

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	**Grain yield**				**Grain Fe content**				**Grain Zn content**			
Locations	**Sadore**		**Gampela**		**Sadore**		**Gampela**		**Sadore**		**Gampela**	
Crosses	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**
ICMX 187812	2.46	0.12	2.54	0.68**	32.60	-3.73*	41.08	-1.26	30.03	-1.91	31.95	-4.74**
ICMX 187813	2.46	0.10	2.49	0.77**	35.93	2.07	33.25	-5.65**	32.00	0.89	31.40	-3.69*
ICMX 187826	1.88	0.03	0.93	-0.31**	35.73	2.50	40.50	-0.76	30.50	-0.17	35.15	-1.48
ICMX 187822	1.59	-0.33**	1.45	0.12	35.50	1.45	47.75	7.44**	32.50	1.42	39.88	3.95*
ICMX 187823	1.81	0.05	1.13	-0.05	40.50	4.73**	42.00	-0.49	30.50	-1.08	37.03	-1.43
ICMX 187824	1.94	0.03	0.90	-0.25*	31.18	-3.22*	46.60	4.78**	26.15	-4.70**	34.78	-1.35
ICMX 187848	1.95	-0.31**	1.62	-1.31**	34.25	-1.78	42.70	0.78	30.50	0.01	37.43	0.69
ICMX 187827	2.89	0.41**	3.08	0.55**	39.78	-2.32	46.83	0.18	34.63	-0.03	43.98	3.92*
ICMX 187829	2.05	-0.35**	3.48	-0.07	45.15	4.01*	39.35	-3.10*	35.13	3.87*	34.60	-4.89**
ICMX 187830	3.03	0.71**	3.40	1.18**	38.45	-2.64	38.13	-3.59*	31.55	-1.16	35.83	-4.07*
ICMX 187832	2.10	-0.04	2.56	0.59**	34.80	-0.05	36.75	-3.40*	29.88	-0.66	34.50	-1.84
ICMX 187788	1.06	-1.06**	1.81	-0.49**	45.38	0.01	51.38	0.32	34.58	-2.85*	39.55	-1.00
ICMX 187836	2.28	-0.24*	2.64	0.00	35.88	-1.85	40.20	-1.51	29.80	-2.24	37.30	0.84
ICMX 187790	2.24	-0.31**	1.64	-0.87**	32.65	-2.61	42.10	3.83*	30.50	-0.71	35.78	0.92
ICMX 187853	2.59	0.56**	1.84	-0.18*	40.23	5.60**	41.23	0.59	33.83	3.06*	36.18	-0.23

Table 6 cont'd. Performance *per se* of crosses and their specific combining ability (*sca*) of pearl millet at Sadore and Gampela.

Traits	**Grain yield**				**Grain Fe content**				**Grain Zn content**			
Locations	**Sadore**		**Gampela**		**Sadore**		**Gampela**		**Sadore**		**Gampela**	
Crosses	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**	**Mean**	**SCA**
ICMX 187849	2.26	0.15	2.33	0.21*	35.98	0.53	41.75	2.06	33.03	1.84	40.78	5.08**
ICMX 187850	1.88	-0.06	2.07	0.11	33.55	-3.62*	40.13	-1.74	31.00	-0.68	33.33	-4.90**
ICMX 187851	2.63	0.54**	2.21	0.28**	40.50	4.71**	46.78	5.58**	30.50	-0.45	41.38	5.47**

*,** F probability significant at P 0.05 and 0.01, respectively

3.1.5. Heterosis over mid-parent and better-parent

Barring a few exceptions all the hybrids at Sadore as well as at Gampela had showed negative heterosis for number of days to 50% flowering and positive heterosis for plant height both over mid parent (MP) and better parent (BP) (Table 7). The heterosis for number of days to 50% flowering ranged from -27.61 (ICMX 187857) to 3.67% (ICMX 187851) over MP and from -34.48 (ICMX 187762) to 0.89% (ICMX 187851) over BP at Sadore whereas it ranged from -26.04 (ICMX 187762) to 2.13% (ICMH 177023) over MP and from -32.19 (ICMX 187769) to 1.70% (ICMH 177023) over BP at Gampela. Regarding plant height, it ranged from 22.73 (ICMX 187990) to 122.47% (ICMX 187856); 0.70 (ICMX 1871005) to 156.10% (ICMX 187762) over MP and from -8.64 (ICMH 177023) to 98.64% (ICMX 187872); -1.36 (ICMX 1871005) to 141.23% (ICMX 187885) over BP at Sadore and Gampela, respectively.

Heterosis for panicle length, ranged from -20.78 (ICMX 187823) to 61.91% (ICMX 187762) over MP and from -28.24 (ICMX 187823) to 58.14% (ICMX 187762) over BP at Sadore while at Gampela, it ranged from -9.09 (ICMH IS 16009) to 117.28% (ICMX 1871029) over MP and from -23.53 (ICMX 187861) to 79.59% (ICMX 1871029) over BP (Table 7). Sixty-nine hybrids showed positive heterosis over the MP as well over BP for panicle length across locations, while, 35 hybrids at Sadore and 33 at Gampela had positive heterosis over MP and 17 hybrids at Sadore and10 at Gampela had positive heterosis over BP. The heterosis varied from -8.11 (ICMX 187853) to 58.33% (ICMH 177019 and ICMX 1871027) over MP and from -19.05 (ICMX 187882, ICMX 187786 and ICMX 187853) to 58.33% (ICMH 177019 and ICMX 1871027) over BP at Sadore whereas at Gampela, it varied from -14.29 (ICMX 1871020) to 50.00% (ICMX 1871030) over MP and from -25.00 (ICMX 1871020) to 50.00% (ICMX 1871030) over BP for panicle circumference. Some 40 hybrids had positive heterosis over MP and BP for panicle circumference across locations; 51 and 18 (over MP), 58 and 25 (over BP) showed positive heterosis for panicle circumference at Sadore and Gampela respectively.

Twenty-two hybrids showed positive heterosis (ranged from 18.57 to 510.70%) over MP and 16 hybrids had positive heterosis (ranged fron 5.42 to 482.65%) over BP at Sadore whereas 14 hybrids exhibited positive heterosis (ranged from 0.66 to 571.29%) over MP and 8 hybrids showed positive heterosis (ranged from 5.03 to 484.48%) over BP showed positive heterosis at Gampela for grain yield (Table 7). ICMH 177016, ICMX 187883, ICMH 177111, ICMX 187857 and ICMX 187865 were the top five hybrids showed positive heterosis at Sadore whereas ICMH 177016, ICMX 187872, ICMX 1871038, ICMX 187864 and ICMX 187812 were the top five hybrids showed positive heterosis for grain yield over MP and BP. Regarding across locations, 85 hybrids exhibited positive heterosis over MP and BP for grain yield.

The positive heterosis for grain Fe, varied from 0.63 to 28.82% (44 hybrids) over MP and from 0.76 to 24.60% (25 hybrids) over BP at sadore, from 0.80 to 30.35% (45 hybrids) over MP and from 0.08 to 30.35% (25 hybrids) over MP at Gampela (Table 7). Eleven hybrids $_{vis}$ ICMH 177017, ICMX 187885, ICMH 177022, ICMX 187998, ICMH 177020, ICMX 187892, ICMX 1871046, ICMH 147009, ICMX 1871029, ICMX 187807 and ICMX 187851 across locations had positive heterosis over MP and BP for grain Fe content. Considering grain Zn content, positive heterosis ranged from 0.06 to 24.34% (26 hybrids) over MP and from 1.19 to 23.01% (10 hybrids) over BP at Sadore. It ranged from 0.42 to 37.62% (41 hybrids) over MP and from 0.76 to 30.86% (23 hybrids) over BP at Gampela. Eleven hybrids $_{vis}$ ICMH 177016, ICMX 187878, ICMH 177111, ICMX 187998, ICMX 187895, ICMX 1871002, ICMX 187870, ICMX 1871046, ICMH 147010, ICMX 1871025, ICMX 1871029, ICMX 187807 and ICMX 187851 across locations had positive heterosis over MP and BP for grain Zn content. Hybrids ICMX 187998, ICMX 1871046, ICMX 1871029, ICMX 187807 and ICMX 187851 had positive heterosis for grain Fe and Zn content over MP and BP across locations.

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMH 177016	-3.00	-3.42	0.86	-0.85	52.32	17.53	53.94	32.29	39.34	18.06	35.71	26.67	44.00	38.46	31.03	11.77
ICMX 187876	-19.67	-23.44	-4.13	-9.38	98.18	98.18	108.95	94.58	8.62	-12.50	9.52	-8.00	22.58	5.56	37.50	10.00
ICMX 187877	-6.51	-15.86	-8.73	-16.67	92.27	92.27	105.93	101.45	11.50	-12.50	4.76	-12.00	15.15	-5.00	29.41	0.00
ICMX 187878	-22.53	-28.47	-11.49	-14.05	91.74	83.75	61.71	51.48	15.00	-4.17	7.58	-5.33	20.00	15.39	11.11	0.00
ICMX 187880	-21.49	-24.60	-7.56	-11.29	85.68	72.94	66.45	48.49	30.58	9.72	23.08	6.67	21.43	13.33	10.35	-5.88
ICMX 187882	-10.41	-14.66	-6.25	-7.90	55.60	50.64	86.09	84.76	14.29	-11.11	20.00	-4.00	0.00	-19.05	9.09	-14.29
ICMH IS 16008	-14.41	-15.52	-18.83	-22.40	70.74	44.06	81.67	54.58	46.15	31.94	29.03	6.67	24.14	12.50	50.00	31.25
ICMH IS 16009	-14.04	-15.52	-10.82	-11.97	62.39	30.14	66.38	30.50	9.52	-4.17	-9.09	-13.33	0.00	-11.77	30.77	21.43
ICMX 187989	-12.07	-12.07	-16.38	-17.80	46.02	37.73	60.22	43.96	13.16	7.50	0.67	0.00	10.35	0.00	23.08	14.29
ICMX 187990	-11.59	-11.97	-4.80	-5.22	22.73	22.73	15.08	10.71	16.18	9.72	3.65	-5.33	13.33	0.00	18.52	6.67
ICMX 187991	-10.44	-11.21	-7.42	-7.83	28.44	25.65	37.32	36.02	13.48	11.11	21.92	18.67	7.14	0.00	21.43	6.25
ICMX 187992	-14.41	-18.10	-13.04	-13.79	47.83	41.67	60.28	56.94	17.99	13.89	18.57	10.67	14.29	6.67	7.14	-6.25
ICMH 177017	-13.49	-19.26	-5.06	-12.23	42.50	12.59	90.38	64.93	29.92	13.43	49.30	37.66	48.15	33.33	9.68	0.00
ICMX 187883	-14.07	-16.30	-13.86	-17.27	97.80	91.49	84.04	72.92	31.53	8.96	10.94	-7.79	15.15	5.56	23.53	5.00
ICMX 187885	-17.14	-20.00	-15.52	-15.83	97.80	91.49	148.90	141.23	25.93	1.49	0.00	-16.88	-2.86	-15.00	16.67	-4.55

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMH 177111	-13.24	-13.87	-10.77	-16.55	105.47	103.33	86.16	75.95	49.57	28.36	16.42	1.30	25.93	13.33	10.35	6.67
ICMH 177022	-13.41	-16.30	-11.79	-16.55	82.04	74.90	90.74	71.59	34.48	16.42	25.76	7.79	13.33	13.33	16.13	5.88
ICMX 187766	-22.50	-31.11	-18.88	-27.34	93.62	93.62	91.92	91.47	36.45	8.96	1.64	-19.48	0.00	-14.29	2.86	-14.29
ICMH IS 16012	-9.68	-17.04	-10.61	-15.11	77.66	54.06	100.00	71.53	52.00	41.79	65.08	35.07	29.03	25.00	40.00	31.25
ICMH IS 16013	-5.26	-13.33	-11.72	-18.71	39.00	14.25	48.87	17.58	14.05	2.99	7.59	1.30	0.00	-5.88	21.43	21.43
ICMX 187995	-6.77	-13.33	-12.06	-18.71	30.70	19.57	81.38	61.61	22.45	12.50	13.91	11.69	-3.23	-6.25	14.29	14.29
ICMX 187996	-4.76	-11.11	-11.02	-18.71	37.14	32.77	50.81	46.43	32.82	29.85	19.42	7.79	6.25	0.00	10.35	6.67
ICMX 187997	-10.84	-17.78	-16.54	-23.74	27.31	25.96	39.81	39.81	29.41	27.54	-4.05	-7.79	6.67	6.67	13.33	6.25
ICMX 187998	-4.56	-14.82	-15.29	-22.30	27.16	25.83	41.45	39.82	17.91	17.91	19.72	10.39	0.00	0.00	13.33	6.25
ICMH 177020	-4.72	-5.13	-1.30	-3.39	38.33	2.47	42.91	26.04	42.34	29.51	33.33	32.31	46.15	35.71	9.09	5.88
ICMX 187891	-9.02	-13.28	-7.88	-13.28	75.90	65.91	67.83	60.83	40.95	21.31	9.57	-1.56	31.25	16.67	16.67	5.00
ICMX 187892	-11.11	-20.00	-8.37	-16.67	91.33	80.46	81.82	72.73	31.37	9.84	14.78	3.13	23.53	5.00	0.00	-13.64
ICMX 187893	-14.63	-21.17	-14.53	-17.36	82.99	65.83	71.99	65.82	39.45	24.59	22.31	15.63	53.85	42.86	16.13	12.50
ICMX 187895	-20.66	-23.81	-8.02	-12.10	93.33	70.59	56.20	43.18	49.09	34.43	32.77	23.44	37.93	33.33	21.21	17.65
ICMX 187897	-10.41	-14.66	-13.00	-14.16	93.02	76.60	90.70	86.36	36.63	13.12	24.77	6.25	20.00	0.00	8.11	-4.76

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 1871001	-15.28	-16.38	-5.04	-9.60	77.09	42.50	56.51	36.61	54.62	50.82	57.52	39.06	13.33	6.25	6.25	6.25
ICMX 1871002	-11.40	-12.93	-1.74	-3.42	81.43	39.18	34.93	8.24	20.00	13.12	21.21	17.65	3.23	-5.88	0.00	-6.25
ICMX 1871003	-11.21	-11.21	-8.23	-10.17	40.00	40.00	46.49	28.18	2.13	-10.00	1.45	-5.41	13.33	6.25	6.67	0.00
ICMX 1871004	-8.16	-8.55	-4.39	-5.22	49.40	40.91	33.33	32.14	21.60	18.75	14.29	12.50	-3.23	-11.77	9.68	6.25
ICMX 1871005	-6.96	-7.76	-8.77	-9.57	16.71	7.83	0.70	-1.36	32.31	24.64	22.96	16.90	10.35	6.67	0.00	0.00
ICMX 1871006	-4.51	-8.62	-16.16	-17.24	21.84	10.42	18.81	17.73	31.25	25.37	27.13	26.15	10.35	6.67	-6.25	-6.25
ICMH 177023	-0.81	-6.11	2.13	1.70	34.55	-8.64	50.20	27.78	23.36	15.79	12.78	10.29	40.74	26.67	22.58	11.77
ICMX 187854	-17.38	-18.32	-11.84	-15.63	110.41	74.55	70.59	57.08	24.75	10.53	7.56	-5.88	21.21	11.11	17.65	0.00
ICMX 187856	-19.57	-23.45	-15.29	-21.74	122.47	84.55	73.00	71.29	34.69	15.79	0.84	-11.77	25.71	10.00	22.22	0.00
ICMX 187857	-27.61	-29.20	-19.33	-20.66	54.29	23.75	43.51	32.91	31.43	21.05	8.80	0.00	18.52	6.67	17.24	13.33
ICMX 187859	-24.51	-25.95	-16.18	-18.55	92.50	50.98	44.21	27.27	26.42	17.54	21.95	10.29	6.67	6.67	29.03	17.65
ICMX 187861	-24.58	-32.06	-18.06	-20.51	92.11	55.32	67.96	64.76	23.71	5.26	-7.97	-23.53	11.11	-4.76	14.29	-4.76
ICMX 1871013	-13.93	-19.85	-15.70	-18.40	85.81	35.00	64.19	38.31	28.70	27.59	16.24	0.00	16.13	12.50	40.00	31.25
ICMX 1871014	-12.76	-19.08	-17.09	-17.09	58.82	10.96	51.59	17.86	31.53	28.07	1.47	1.47	0.00	-5.88	14.29	14.29
ICMH 177002	-16.60	-21.37	-13.19	-13.56	63.53	42.56	51.50	37.62	35.77	16.25	12.68	8.11	16.13	12.50	21.43	21.43

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 1871008	-21.77	-25.95	-14.66	-15.39	53.97	27.73	32.86	26.34	20.66	14.06	6.15	1.47	-6.25	-11.77	24.14	20.00
ICMX 1871009	-23.27	-28.24	-6.03	-6.84	38.67	13.04	27.85	25.12	-6.35	-14.49	-2.16	-4.23	6.67	6.67	20.00	12.50
ICMX 1871010	-20.68	-28.24	-0.43	-0.86	51.69	21.67	27.75	23.61	38.71	28.36	8.27	5.88	13.33	13.33	6.67	0.00
ICMX 1871038	-3.61	-9.09	-8.71	-10.57	30.54	-3.95	80.14	38.54	28.93	9.86	24.03	23.08	47.83	41.67	17.24	0.00
ICMX 187862	-14.62	-15.91	-7.57	-9.38	86.38	74.09	94.94	60.42	18.26	-4.23	23.48	10.94	24.14	0.00	25.00	0.00
ICMX 187864	-10.47	-14.48	-1.15	-6.52	108.27	94.55	144.76	118.18	25.00	-1.41	23.48	10.94	22.58	-5.00	11.77	-13.64
ICMX 187865	-27.14	-28.47	-12.30	-13.01	101.86	81.25	103.57	68.35	32.77	11.27	22.31	15.63	30.44	25.00	3.70	-6.67
ICMX 187867	-18.61	-20.46	-13.36	-13.71	71.30	49.80	106.21	63.64	20.00	1.41	19.33	10.94	23.08	6.67	24.14	5.88
ICMX 187868	-20.68	-28.79	-10.73	-15.45	92.49	74.47	80.27	56.67	17.12	-8.45	22.94	4.69	18.75	-9.52	15.15	-9.52
ICMH 147008	-7.76	-14.39	-14.52	-15.20	82.39	45.63	105.33	56.61	34.88	22.54	66.37	46.88	33.33	12.50	28.57	12.50
ICMX 1871017	-18.03	-24.24	-10.83	-13.01	69.78	29.32	82.27	29.95	23.20	8.45	16.67	13.24	14.29	-5.88	30.77	21.43
ICMX 1871018	2.42	-3.79	-5.39	-7.32	32.12	30.77	58.13	53.33	-8.61	-13.75	-1.45	-8.11	3.70	-12.50	15.39	7.14
ICMX 1871019	-2.81	-8.33	-2.52	-5.69	41.12	31.82	46.17	23.66	8.15	2.82	30.16	28.13	0.00	-17.65	25.93	13.33
ICMX 1871020	-21.14	-26.52	-5.88	-8.94	35.39	23.91	33.33	15.64	10.00	8.45	2.22	-2.82	15.39	0.00	-14.29	-25.00
ICMX 1871021	-9.24	-18.18	-3.77	-6.50	29.93	16.67	50.40	29.17	18.84	15.49	14.73	13.85	23.08	6.67	7.14	-6.25

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMH 177018	-8.27	-18.12	-13.64	-21.92	32.77	-2.47	84.10	52.78	32.11	22.03	35.39	35.39	44.00	38.46	16.13	5.88
ICMX 187870	-21.30	-26.85	-22.63	-27.40	110.24	95.91	97.67	77.08	35.92	18.64	12.07	0.00	22.58	5.56	23.53	5.00
ICMX 187872	-23.81	-24.83	-21.13	-23.29	113.17	98.64	90.72	86.87	46.00	23.73	32.76	18.46	15.15	-5.00	11.11	-9.09
ICMX 1871046	-23.08	-26.18	-22.85	-29.45	39.54	25.00	67.68	51.06	42.06	28.81	42.62	33.85	28.00	23.08	10.35	6.67
ICMX 187875	-22.91	-28.86	-20.74	-26.71	106.74	80.39	42.73	22.73	61.11	47.46	43.33	32.31	0.00	-6.67	3.23	-5.88
ICMX 187769	-13.39	-26.18	-22.66	-32.19	106.59	86.81	57.50	50.00	11.11	-6.78	14.55	-3.08	5.88	-14.29	-8.57	-23.81
ICMH 147010	-12.21	-22.82	-20.30	-26.03	90.20	51.56	76.08	44.75	17.95	16.95	36.84	20.00	37.93	25.00	26.67	18.75
ICMH 147009	-15.71	-26.18	-14.83	-23.29	40.18	6.58	48.74	13.19	29.20	23.73	12.78	10.29	13.33	0.00	28.57	28.57
ICMX 1871023	-15.47	-24.83	-13.64	-21.92	48.05	46.15	93.24	80.53	32.37	15.00	6.48	0.00	17.24	6.25	7.14	7.14
ICMX 1871024	-16.54	-25.50	-14.94	-23.97	37.07	27.73	30.44	20.54	7.32	3.13	33.86	30.77	6.67	-5.88	3.45	0.00
ICMX 1871025	-16.35	-26.18	-17.24	-26.03	59.52	45.65	57.11	49.29	23.44	14.49	29.41	23.94	7.14	0.00	0.00	-6.25
ICMX 1871029	-14.51	-26.85	-17.56	-26.03	63.26	46.25	46.31	37.50	7.94	1.49	12.31	12.31	28.57	20.00	6.67	0.00
ICMH 177019	-9.87	-10.26	-18.37	-21.26	25.64	-8.64	47.37	6.94	37.63	28.00	36.08	1.54	58.33	58.33	29.03	17.65
ICMX 187068	-22.95	-26.56	-23.14	-23.44	85.15	70.00	62.70	25.42	44.83	43.18	49.40	21.57	20.00	0.00	0.00	-15.00
ICMX 187762	-27.20	-34.48	-26.04	-28.99	100.00	83.64	156.10	112.12	61.91	58.14	51.81	23.53	31.25	5.00	22.22	0.00

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 1871027	-21.74	-27.74	-23.39	-25.20	72.17	52.08	105.45	59.07	56.04	47.92	66.29	29.83	58.33	58.33	10.35	6.67
ICMX 187763	-20.66	-23.81	-12.35	-13.39	66.29	43.14	70.05	26.89	15.22	8.16	42.53	12.73	40.74	26.67	16.13	5.88
ICMX 187765	-11.31	-15.52	-19.83	-25.20	81.86	62.13	94.12	57.14	42.17	37.21	50.65	28.89	15.15	-9.52	8.57	-9.52
ICMX 1871029	-20.52	-21.55	-24.60	-25.20	67.46	31.88	60.47	15.59	40.59	22.41	117.28	79.59	35.71	18.75	13.33	6.25
ICMX 1871030	-14.91	-16.38	-23.77	-26.77	31.15	-1.37	63.56	10.99	48.45	33.33	44.00	5.88	3.45	-11.77	50.00	50.00
ICMX 1871032	-11.21	-11.21	-16.74	-19.69	53.56	49.23	72.88	54.55	20.33	-7.50	24.53	-10.81	14.29	0.00	14.29	14.29
ICMX 1871033	-19.31	-19.66	-8.26	-12.60	42.08	30.46	63.84	29.46	25.23	4.69	34.04	1.61	3.45	-11.77	31.03	26.67
ICMX 1871034	-14.78	-15.52	-20.66	-24.41	37.68	23.91	54.25	24.65	25.00	1.45	28.16	-7.04	25.93	13.33	13.33	6.25
ICMX 1871035	-11.71	-15.52	-12.76	-16.54	66.51	47.08	44.51	15.74	49.09	22.39	64.95	23.08	18.52	6.67	0.00	-6.25
ICMX 187825	-13.12	-16.54	-13.12	-15.87	39.33	3.21	76.14	40.97	21.48	-3.53	2.19	-2.78	36.00	30.77	18.75	11.77
ICMX 187803	-19.22	-19.53	-13.39	-14.06	98.55	87.27	104.36	75.83	31.78	0.00	28.46	9.72	16.13	0.00	2.86	-10.00
ICMX 187806	-14.71	-20.00	-13.64	-17.39	99.04	87.73	120.49	106.57	20.64	-10.59	28.46	9.72	21.21	0.00	13.51	-4.55
ICMX 187807	-28.03	-30.66	-21.46	-23.02	105.98	86.67	84.88	59.92	33.84	4.71	31.78	18.06	20.00	15.39	13.33	13.33
ICMX 187808	-16.21	-16.54	-16.80	-17.46	74.67	54.12	48.74	23.11	16.42	-8.24	11.81	-1.39	14.29	6.67	6.25	0.00
ICMX 187786	-16.38	-23.62	-15.25	-20.64	109.30	91.49	81.20	65.24	10.40	-18.82	24.79	1.39	0.00	-19.05	-11.11	-23.81

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 187812	-6.67	-11.81	-16.34	-16.67	77.09	42.50	106.41	63.73	18.88	0.00	57.03	31.94	24.14	12.50	16.13	12.50
ICMX 187813	-16.32	-21.26	-11.11	-14.29	55.00	18.90	59.40	17.58	-7.91	-24.71	5.71	2.78	13.33	0.00	37.93	33.33
ICMX 187826	-16.05	-19.69	-16.39	-19.05	65.13	65.13	95.27	90.75	5.46	2.35	9.59	8.11	17.24	6.25	17.24	13.33
ICMX 187822	-11.48	-14.96	-9.54	-13.49	58.55	49.55	45.09	28.57	7.38	-5.88	44.78	34.72	0.00	-11.77	6.67	6.67
ICMX 187823	-17.84	-22.05	-15.35	-19.05	39.29	28.70	22.40	11.37	-20.78	-28.24	0.70	0.00	21.43	13.33	9.68	6.25
ICMX 187824	-15.88	-22.84	-12.40	-15.87	33.79	21.25	43.45	29.17	18.42	5.88	45.99	38.89	21.43	13.33	3.23	0.00
ICMX 187848	2.18	0.00	-9.01	-10.17	8.40	-4.44	16.21	8.06	5.38	-2.00	11.67	3.08	33.33	4.76	8.11	0.00
ICMX 187827	-11.67	-17.19	-14.40	-18.75	70.89	46.28	44.70	24.18	28.74	27.27	5.66	1.82	7.69	0.00	15.00	15.00
ICMX 187829	-12.06	-22.07	-15.42	-22.46	43.67	22.98	57.60	25.37	28.57	25.58	3.77	0.00	7.32	4.76	14.29	9.09
ICMX 187830	-18.07	-25.55	-9.32	-11.57	71.59	52.43	63.64	39.70	49.45	41.67	30.36	28.07	21.21	-4.76	8.57	-5.00
ICMX 187832	-10.92	-15.87	-13.81	-16.94	55.32	41.75	53.92	37.61	50.00	40.82	9.09	9.09	11.11	-4.76	18.92	10.00
ICMX 187788	-13.36	-16.07	-15.56	-17.39	66.54	46.60	66.61	35.52	42.17	37.21	22.00	10.91	-4.76	-4.76	7.32	4.76
ICMX 187836	-10.22	-10.62	-12.50	-16.00	47.54	45.00	25.71	18.21	20.79	5.17	17.31	10.91	2.70	-9.52	27.78	15.00
ICMX 187790	2.68	2.68	-6.90	-7.69	37.98	27.40	23.03	18.13	17.53	5.56	-4.07	-13.24	-5.26	-14.29	23.53	5.00
ICMX 187853	-7.02	-8.62	-5.58	-6.78	78.57	45.63	53.60	14.63	4.07	-20.00	19.38	4.05	-8.11	-19.05	5.88	-10.00

Table 7. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Days to 50% flowering				Plant height				Panicle length				Panicle circumference			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 187849	-13.54	-15.39	-13.04	-13.04	78.45	52.75	48.48	23.88	25.23	4.69	5.98	0.00	0.00	-9.52	14.29	0.00
ICMX 187850	-8.85	-9.65	-15.65	-15.65	52.88	33.33	61.91	31.94	8.93	-11.59	4.76	-7.04	11.11	-4.76	5.56	-5.00
ICMX 187851	3.67	0.89	-2.17	-2.59	48.63	32.04	36.12	11.94	27.27	4.48	33.33	23.08	5.56	-9.52	5.56	-5.00

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMH 177016	159.44	69.41	359.61	275.64	9.93	-6.93	5.29	-7.18	24.34	23.01	18.04	7.70
ICMX 187876	412.82	349.44	303.69	271.19	-14.49	-17.36	-12.76	-13.54	-9.85	-17.57	-19.87	-24.11
ICMX 187877	183.42	113.64	390.23	354.31	-12.56	-18.55	-4.15	-12.72	-6.73	-13.01	-5.89	-9.46
ICMX 187878	356.16	321.52	254.26	236.36	5.11	-8.13	-3.09	-15.42	15.25	11.35	14.62	0.80
ICMX 187880	95.30	25.97	-36.30	-49.71	-14.34	-26.83	-13.11	-22.05	-14.70	-17.54	-6.52	-13.79
ICMX 187882	192.49	138.68	234.43	209.09	-23.81	-30.99	-22.98	-28.35	-9.44	-25.49	-16.12	-16.30
ICMH IS 16008	52.20	-9.89	142.34	118.70	1.43	-15.21	-8.02	-14.78	11.53	6.92	4.85	-2.41
ICMH IS 16009	67.01	-3.30	80.12	28.33	-8.26	-22.20	-15.78	-25.89	3.89	1.35	-11.83	-20.90
ICMX 187989	116.38	52.12	81.67	50.00	-17.46	-27.03	-9.07	-18.12	-2.47	-5.04	-2.41	-13.42
ICMX 187990	237.10	130.94	33.03	20.49	-19.92	-29.33	-16.69	-24.06	-6.32	-7.35	-10.61	-19.83
ICMX 187991	153.33	101.77	64.17	39.72	-4.94	-13.62	5.63	-4.67	-2.12	-4.36	15.23	-1.12
ICMX 187992	124.43	50.77	41.05	11.83	2.08	-14.36	-1.55	-18.57	17.65	12.78	-8.12	-24.11
ICMH 177017	155.52	84.93	196.58	177.56	28.82	24.60	9.16	6.90	1.48	-1.28	-12.73	-14.45
ICMX 187883	510.70	482.65	207.09	186.77	14.97	-7.77	8.72	-1.58	-2.54	-13.89	26.72	19.49
ICMX 187885	378.26	316.67	376.98	341.91	17.07	2.49	19.89	18.05	-3.18	-12.82	26.81	17.76
ICMH 177111	494.35	436.74	156.89	112.50	27.76	19.20	-0.89	-4.02	13.96	13.55	31.43	28.68

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMH 177022	148.02	76.62	120.85	98.25	7.39	2.82	7.54	7.41	-2.11	-8.77	12.61	9.11
ICMX 187766	331.37	315.09	150.91	102.94	-3.50	-26.38	2.80	-13.39	-5.38	-24.42	10.73	-0.59
ICMH IS 16012	79.65	14.01	158.69	146.32	16.33	14.25	2.64	-0.80	6.08	5.61	4.01	-0.19
ICMH IS 16013	114.56	32.08	64.77	30.47	8.13	4.37	-13.85	-15.81	-3.85	-5.14	-11.32	-11.44
ICMX 187995	258.18	185.46	100.00	89.47	-3.84	-11.36	2.09	1.77	-3.65	-4.76	11.91	10.66
ICMX 187996	135.13	81.22	94.57	84.56	14.58	5.80	-0.76	-2.39	-0.81	-5.52	8.19	8.08
ICMX 187997	261.14	237.17	146.21	141.84	-7.83	-17.39	-15.49	-15.97	0.80	-0.71	-3.90	-8.50
ICMX 187998	171.67	104.10	50.16	35.50	6.92	4.56	12.93	2.87	3.88	3.41	19.91	9.31
ICMH 177020	115.63	57.53	15.39	-15.68	8.43	-4.98	13.36	9.50	-7.43	-15.07	4.50	2.40
ICMX 187891	354.74	327.72	33.77	-9.76	-14.92	-20.89	-12.62	-19.89	-13.59	-14.83	-15.03	-19.90
ICMX 187892	334.34	283.33	153.30	70.12	15.40	11.75	14.53	14.37	-16.02	-16.61	21.50	12.78
ICMX 187893	240.00	202.97	-10.54	-43.49	18.67	7.53	-0.59	-5.03	-0.61	-10.78	-2.10	-4.12
ICMX 187895	265.06	162.34	2.55	-22.78	10.68	-2.11	6.64	5.03	15.21	10.26	7.94	4.56
ICMX 187897	277.78	268.87	107.58	29.59	-0.37	-12.94	21.94	3.94	-6.05	-17.48	5.26	-5.53
ICMX 1871001	114.19	36.81	21.04	-17.46	8.52	-6.17	-5.88	-7.78	8.17	-3.59	-8.18	-11.91
ICMX 1871002	60.76	-0.47	24.34	5.03	2.74	-9.80	3.56	-0.17	12.39	1.80	15.20	15.01

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 1871003	188.72	132.73	27.35	-7.69	-17.10	-23.99	4.21	3.07	-7.77	-16.61	15.22	13.98
ICMX 1871004	115.60	67.96	-1.30	-32.84	-23.81	-30.27	-25.33	-25.51	-15.59	-20.98	-15.04	-15.15
ICMX 1871005	186.92	171.68	-8.56	-35.21	-6.02	-11.32	15.72	14.75	-11.53	-19.76	37.40	30.86
ICMX 1871006	101.35	52.82	-4.93	-28.70	12.35	-2.49	5.59	-5.03	-1.91	-12.57	5.15	-4.12
ICMH 177023	105.59	34.25	131.58	112.90	-14.46	-22.98	-5.95	-16.41	-16.24	-24.35	-1.95	-13.88
ICMX 187854	382.05	322.47	208.55	152.15	-24.89	-32.11	1.03	0.98	-26.06	-26.27	2.53	-6.67
ICMX 187856	322.11	218.18	333.78	252.15	8.83	8.64	-18.83	-25.46	-15.65	-17.66	-21.66	-27.61
ICMX 187857	463.01	420.25	83.27	35.48	7.17	-0.12	-5.91	-17.20	-10.44	-20.82	-0.09	-15.25
ICMX 187859	105.37	32.47	-36.70	-39.25	-9.00	-17.28	-11.98	-20.37	-17.14	-22.00	-12.90	-22.71
ICMX 187861	340.46	259.43	71.11	24.19	-3.40	-17.76	8.52	0.08	-26.84	-34.76	-10.10	-13.98
ICMX 1871013	113.92	26.65	155.02	111.83	7.69	-4.38	-3.79	-10.07	-11.08	-21.93	-5.83	-15.69
ICMX 1871014	101.63	16.75	80.91	62.66	-1.28	-10.95	-11.61	-21.59	-10.66	-20.32	-7.69	-20.21
ICMH 177002	106.04	44.85	6.51	-3.23	-18.80	-23.39	-8.21	-16.64	-11.76	-21.44	-11.41	-24.23
ICMX 1871008	175.81	88.95	49.35	23.66	-12.48	-17.57	-7.86	-15.29	-15.00	-21.69	3.75	-10.35
ICMX 1871009	105.56	63.72	-3.36	-15.05	-4.00	-6.68	2.79	-6.43	-9.82	-19.46	14.24	-5.35
ICMX 1871010	209.16	107.69	-20.56	-24.19	-10.44	-20.16	1.87	-15.11	-13.90	-24.41	8.87	-13.00

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 1871038	297.40	179.45	482.28	342.31	-27.63	-33.47	-21.64	-29.81	-29.65	-30.94	-17.36	-26.42
ICMX 187862	357.30	357.30	183.42	138.98	-12.06	-22.10	-19.89	-20.63	1.69	-6.36	-19.70	-25.86
ICMX 187864	274.66	213.64	469.54	383.62	-15.17	-16.94	-8.15	-14.95	-9.97	-15.42	-9.10	-14.78
ICMX 187865	442.86	412.36	201.18	187.64	0.63	-4.16	2.49	-9.11	-0.12	-4.22	3.95	-10.68
ICMX 187867	199.38	107.36	96.83	45.03	-21.57	-27.20	-11.42	-19.22	-27.09	-28.98	-13.50	-22.17
ICMX 187868	218.97	193.40	267.27	260.71	-0.21	-16.63	-9.28	-17.01	3.72	-14.13	-11.33	-13.87
ICMH 147008	130.02	43.13	350.98	273.98	-8.22	-16.83	-9.92	-15.09	-4.32	-8.96	-10.03	-18.32
ICMX 1871017	76.61	6.84	161.78	76.40	-10.94	-17.97	0.80	-9.87	-6.73	-9.70	-3.52	-15.49
ICMX 1871018	104.72	57.58	161.80	100.66	-12.45	-15.56	-12.39	-19.79	-6.55	-9.70	-12.41	-24.09
ICMX 1871019	154.07	89.50	148.28	106.56	-18.55	-21.59	-4.46	-11.44	-10.00	-10.29	-10.43	-21.56
ICMX 1871020	268.32	229.20	60.36	26.24	4.40	3.80	-6.18	-13.91	16.64	13.10	0.42	-15.74
ICMX 1871021	142.96	76.92	139.20	76.92	-4.54	-13.15	-12.02	-26.15	6.73	1.55	-13.52	-30.06
ICMH 177018	155.15	75.34	184.30	120.51	-10.64	-12.16	15.87	15.59	-12.53	-14.80	18.80	14.06
ICMX 187870	332.75	315.73	246.08	199.15	7.69	-10.10	10.27	-2.24	22.37	8.22	14.97	6.28
ICMX 187872	353.27	267.42	571.29	484.48	-8.62	-16.30	-5.53	-9.08	-31.36	-38.13	-6.19	-14.58
ICMX 1871046	250.31	243.90	154.86	150.56	6.77	4.60	12.40	11.39	14.31	14.03	12.54	12.54

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 187875	150.48	69.70	105.45	54.39	-0.53	-1.18	0.88	-1.33	-15.98	-21.61	6.13	0.76
ICMX 187769	412.77	354.72	302.35	297.67	-9.46	-28.36	6.67	-11.81	-15.18	-32.18	21.29	6.87
ICMH 147010	87.44	14.84	189.95	146.34	22.33	18.42	4.23	-1.50	11.25	10.62	12.53	5.83
ICMH 147009	65.61	-1.18	67.40	14.59	2.43	0.90	1.36	1.33	-8.92	-10.04	9.70	7.27
ICMX 1871023	138.06	78.18	116.81	69.74	-3.79	-6.95	2.08	-0.57	0.88	-0.16	11.33	10.21
ICMX 1871024	201.14	118.79	186.54	144.26	12.61	9.13	-5.18	-8.84	8.40	3.38	0.52	-1.68
ICMX 1871025	321.54	263.72	105.29	65.25	-14.56	-19.77	-0.59	-3.41	1.16	-0.24	5.80	2.82
ICMX 1871029	86.28	32.31	125.88	70.41	3.65	0.76	10.03	2.41	12.31	11.67	18.18	9.86
ICMH 177019	47.49	20.55	117.99	101.92	18.69	7.81	-0.74	-10.88	-5.72	-12.65	-16.45	-23.49
ICMX 187068	142.98	99.28	24.30	17.29	-4.65	-14.57	-4.78	-5.92	-9.29	-11.53	-9.32	-13.79
ICMX 187762	104.43	99.28	162.65	145.87	2.33	1.50	-8.51	-15.08	-12.83	-13.14	-6.95	-10.13
ICMX 1871027	101.84	58.27	46.85	22.56	5.18	-1.06	5.85	-5.92	-8.68	-17.24	14.41	0.97
ICMX 187763	-35.14	-48.05	0.66	-10.53	3.97	-4.64	-10.23	-17.94	-11.89	-14.81	-23.17	-28.88
ICMX 187765	331.84	280.58	183.87	131.58	-10.85	-24.72	-8.11	-16.14	-17.85	-28.50	-3.63	-3.81
ICMX 1871029	68.19	16.21	174.22	163.91	10.00	-1.47	-10.73	-15.65	-0.58	-10.55	-22.72	-27.80
ICMX 1871030	24.33	-17.45	83.06	43.78	-5.81	-14.28	-13.71	-22.66	-9.71	-17.43	-19.57	-27.59

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 1871032	120.40	103.03	31.93	23.68	-2.47	-7.11	-10.84	-18.18	-6.82	-14.94	-6.87	-17.08
ICMX 1871033	122.50	96.69	145.49	135.34	6.18	0.94	-16.82	-22.71	-14.00	-18.68	-22.18	-29.96
ICMX 1871034	177.78	151.80	71.53	66.67	-4.94	-6.70	-14.99	-21.80	-1.83	-10.09	1.75	-12.39
ICMX 1871035	90.42	63.08	-9.93	-19.53	-11.60	-20.51	-1.36	-17.03	-21.85	-29.69	2.73	-14.87
ICMX 187825	163.04	121.01	372.57	258.97	-12.47	-15.38	-5.75	-12.47	-4.75	-6.27	-7.90	-15.75
ICMX 187803	332.77	245.64	114.07	80.51	-3.63	-18.43	22.90	2.38	2.76	-8.29	37.62	21.46
ICMX 187806	215.30	197.32	338.58	272.41	-3.14	-9.88	12.74	1.28	-9.90	-18.02	14.66	-0.23
ICMX 187807	344.74	240.27	228.24	213.48	8.00	7.60	14.51	7.49	3.20	2.38	20.74	14.79
ICMX 187808	57.90	29.87	90.48	40.35	-12.00	-14.04	6.13	-3.23	-9.13	-14.39	9.37	-1.01
ICMX 187786	117.26	85.91	199.39	194.05	-15.70	-32.45	-17.53	-35.55	-2.47	-21.41	-6.14	-20.83
ICMX 187812	91.81	35.17	397.06	312.20	-8.04	-12.42	-0.27	-11.90	-3.15	-4.68	-11.62	-20.72
ICMX 187813	71.73	16.04	216.56	113.31	-0.38	-3.49	-13.94	-19.93	1.39	1.19	-9.18	-15.48
ICMX 187826	138.85	127.27	59.66	22.37	-5.65	-7.21	1.86	-7.48	-3.18	-3.18	3.04	-2.97
ICMX 187822	92.73	75.69	184.73	136.89	-6.05	-7.43	18.30	6.17	-0.76	-4.41	15.37	7.41
ICMX 187823	176.34	142.95	102.70	59.57	3.58	-1.16	5.33	-4.55	-3.52	-3.86	13.05	10.52
ICMX 187824	125.58	98.97	44.00	6.51	-12.43	-16.25	30.35	30.35	-15.65	-16.98	11.28	8.67

Table 7 cont'd. Heterosis over mid parent and better parent of pearl millet at Sadore and Gampela.

Cross	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore		Gampela		Sadore		Gampela		Sadore		Gampela	
	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)	MPH (%)	BPH (%)
ICMX 187848	42.08	18.18	58.33	28.18	-3.32	-5.13	3.96	2.40	0.06	-6.27	-0.10	-2.98
ICMX 187827	175.42	74.85	232.43	144.05	-11.44	-25.97	-0.51	-12.76	1.02	-13.71	12.50	5.14
ICMX 187829	77.49	24.24	277.72	175.79	13.80	4.39	-7.76	-12.31	5.09	-8.59	-13.04	-19.95
ICMX 187830	195.84	83.33	298.83	169.84	4.48	2.53	-6.10	-6.44	6.18	1.77	-0.28	-1.44
ICMX 187832	49.73	27.27	142.08	103.18	-2.79	-3.60	-12.34	-15.32	-6.71	-16.14	-9.03	-12.66
ICMX 187788	-3.21	-36.06	115.48	43.65	-7.28	-26.54	-1.15	-19.09	-13.48	-32.86	-4.61	-15.08
ICMX 187836	31.41	25.28	181.60	109.52	2.83	-0.62	-7.67	-13.78	1.15	-2.30	-2.67	-7.44
ICMX 187790	18.57	5.43	34.85	29.76	-8.03	-9.56	2.71	1.39	1.58	-3.56	-2.65	-3.70
ICMX 187853	108.89	56.67	82.18	46.03	7.84	4.48	-2.11	-5.83	12.89	7.38	-0.31	-0.48
ICMX 187849	76.52	36.67	148.66	84.52	-3.36	-6.19	-2.25	-7.17	5.81	-2.87	10.99	9.83
ICMX 187850	69.75	13.94	110.69	64.29	-12.94	-18.12	-4.97	-8.81	3.08	-2.29	-4.58	-8.32
ICMX 187851	100.00	59.09	109.98	75.40	15.59	12.19	22.77	15.64	3.52	0.00	23.79	13.82

3.2. Improvement of Restorer Lines for Strengthening Pearl Millet (*Pennisetum glaucum* L.) Hybrid Breeding at Sadore (Niger)

3.2.1. Mean performance of pearl millet restorer lines and their crosses for agronomic and morphological traits

Analysis of variance revealed significant differences ($P \leq 0.05$) among the genotypes for all the traits examined, indicating presence of significant variability in the restorer lines tested and can be exploited through selection (Table 8). The overall mean was 66.53 days (ranging from 47 to 88 days) for number of days to 50% flowering. ICMR 157003 exhibited early flowering of 65 days. Thirteen F1 progenies also exhibited early flowering. The cross ICMX 1770217 showed early flowering of 46.67 days, whose parents were ICMR 167011 and ICMR 157003.

Parents ICMR 157001, ICMR 157005, and ICMR 167011 exhibited medium plant height along with twelve hybrids (Table 8). Twenty crosses exhibited longer length of panicles, when compared to the mean of 39 cm and fourteen crosses exhibited higher panicle circumference of, more than 8 cm. The cross ICMX 1770192 (2.19 t/ha), ICMX 1770197 (2.14 t/ha) and ICMX 1770193 (2.08 t/ha) exhibited high grain yield with early days to 50% flowering and medium plant height. The parents ICMR 157004 (9.87 t/ha) and ICMR 157002 (8.50 t/ha) produced high biomass yield. Eighteen hybrids showed high grain yield along with the biomass yield. All the parental genotypes used in the study had low to medium grain Fe content ranging between 34-47 ppm but, the crosses ICMX 1770206 (Fe = 70.00 mg/kg; Zn = 63.00 mg/kg) and ICMX 1770217 (Fe = 69.00 mg/kg and Zn = 53.00 mg/kg) showed high grain Fe and Zn contents.

Table 8. Mean performance of restorer lines (parents) and their F1's for morphological and agronomic traits of pearl millet at Sadore.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Biomass yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
Direct crosses								
ICMX 1770190	76.00	231.00	54.00	7.00	1.13	8.60	41.00	33.00
ICMX 1770191	55.00	209.00	50.00	8.00	1.98	6.70	37.00	33.00
ICMX 1770192	62.00	204.00	44.00	8.00	2.19	7.52	39.00	38.00
ICMX 1770193	58.00	212.00	44.00	8.00	2.08	5.94	38.00	36.00
ICMX 1770194	58.00	199.00	47.00	8.00	1.88	5.43	35.00	32.00
ICMX 1770196	75.00	229.00	46.00	9.00	1.78	12.57	42.00	37.00

Table 8. Mean performance of restorer lines (parents) and their F1's for morphological and agronomic traits of pearl millet at Sadore.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Biomass yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
ICMX 1770197	63.00	211.00	48.00	9.00	2.14	5.98	34.00	30.00
ICMX 1770198	77.00	237.00	40.00	8.00	1.35	13.77	43.00	34.00
ICMX 1770199	74.00	245.00	42.00	9.00	1.65	12.48	42.00	40.00
ICMX 1770202	68.00	124.00	43.00	7.00	0.68	1.84	41.00	32.00
ICMX 1770203	69.00	135.00	41.00	7.00	0.71	2.19	43.00	37.00
ICMX 1770204	67.00	177.00	24.00	9.00	0.97	2.36	38.00	34.00
ICMX 1770208	52.00	129.00	21.00	9.00	0.67	1.86	46.00	41.00
ICMX 1770209	71.00	204.00	40.00	8.00	1.92	7.39	37.00	32.00
ICMX 1770214	63.00	188.00	30.00	9.00	0.89	2.41	34.00	27.00
Reciprocals								
ICMX 1770195	74.00	238.00	55.00	7.00	1.37	9.11	38.00	34.00
ICMX 1770200	66.00	153.00	37.00	8.00	0.57	2.60	46.00	41.00
ICMX 1770201	64.00	135.00	38.00	8.00	0.57	1.45	46.00	42.00
ICMX 1770205	73.00	239.00	40.00	9.00	1.51	10.28	43.00	33.00
ICMX 1770206	52.00	113.00	19.00	10.00	0.10	0.47	70.00	63.00
ICMX 1770207	61.00	214.00	42.00	9.00	1.61	6.83	39.00	31.00
ICMX 1770210	61.00	196.00	32.00	9.00	1.06	3.55	43.00	33.00
ICMX 1770211	77.00	251.00	42.00	9.00	1.26	11.67	43.00	36.00
ICMX 1770212	65.00	229.00	43.00	9.00	1.71	6.06	32.00	29.00
ICMX 1770213	70.00	175.00	32.00	8.00	1.06	5.09	36.00	31.00
ICMX 1770215	60.00	210.00	46.00	8.00	1.89	5.98	38.00	31.00
ICMX 1770216	76.00	240.00	51.00	7.00	1.44	9.03	44.00	34.00
ICMX 1770217	47.00	117.00	20.00	9.00	0.14	1.43	69.00	53.00
ICMX 1770218	67.00	212.00	42.00	8.00	1.75	6.68	41.00	37.00
ICMX 1770219	67.00	157.00	19.00	10.00	0.42	1.50	41.00	36.00
Parents								
ICMR 157001	71.00	138.00	40.00	6.00	0.46	1.44	34.00	30.00

Table 8. Mean performance of restorer lines (parents) and their F1's for morphological and agronomic traits of pearl millet at Sadore.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Biomass yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
ICMR 157002	88.00	243.00	45.00	8.00	0.32	8.50	47.00	37.00
ICMR 157003	65.00	198.00	39.00	8.00	0.78	4.39	42.00	39.00
ICMR 157004	66.00	216.00	47.00	9.00	1.68	9.87	40.00	34.00
ICMR 157005	71.00	131.00	27.00	9.00	0.33	1.08	43.00	40.00
ICMR 167011	67.00	147.00	39.00	8.00	1.48	2.93	41.00	35.00
Fpr	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Vr	**24.54**	**25.86**	**18.75**	**4.16**	**6.70**	**10.49**	**8.63**	**5.50**
Mean	**66.53**	**191.00**	**39.00**	**8.00**	**1.21**	**5.75**	**42.00**	**36.00**
SE	**1.68**	**8.40**	**2.20**	**0.40**	**0.24**	**1.16**	**2.60**	**2.80**
LSD	**4.73**	**23.70**	**6.30**	**1.20**	**0.68**	**3.26**	**7.40**	**7.90**
CV (%)	**4.40**	**7.60**	**9.90**	**8.70**	**34.40**	**34.80**	**10.90**	**13.50**

3.2.2. Combining ability studies

3.2.2.1. Analysis of variance for combining ability

The mean sum of squares for general combining ability (GCA) of parents and specific combining ability (SCA) for the crosses showed significant ($P \leq 0.01$) probabilities for all the studied traits (Table 9). The mean sum of squares for the reciprocal crosses was significant at $P \leq 0.01$ for all the traits. The magnitude of mean sum of squares of GCA for days to 50% flowering, plant height, panicle length, panicle circumference, biomass yield and grain Fe content was high. Mean sum of squares for panicle circumference, grain yield and biomass yield exhibited significant probabilities for the maternal effects indicating the influence of the maternal factors in inheritance of these traits.

The variance due to SCA (σ^2SCA) was higher in magnitude than the variance due to GCA (σ^2GCA) for all the studied traits (Table 9). The ratio of σ^2GCA to σ^2SCA is less than one indicating predominance of dominant gene action in inheritance of these traits. The predictability ratio is less than one for all the traits. The narrow sense heritability was high for days to 50% flowering (76%) and panicle length (71%), medium for plant height (53%), panicle circumference (60%), biomass yield (59%), and grain Fe content (48%).

Table 9. Analysis of variance (ANOVA) showing the mean sum of squares of general, specific and reciprocal combining abilities of R × R diallel of pearl millet at Sadore.

Sources of variation	df	Days to 50% flowering	Plant height	Panicle length	Panicle circumference	Grain yield	Biomass yield	Grain Fe content	Grain Zn content
Due to GCA	5	476.96**	7962.39**	626.97**	3.85**	1.28**	80.81**	145.42**	87.60**
Due to SCA	15	190.75**	5415.98**	277.82**	1.90**	1.05**	45.62**	99.78**	87.46**
Due to reciprocals	15	132.81**	4721.40**	159.74**	1.47**	1.22**	25.38**	263.68**	187.70**
Maternal effect	5	139.28	7344.41	220.66	2.53*	2.19**	55.08**	347.58	180.76
Maternal interaction	10	129.58**	3409.89**	129.29**	0.93	0.74**	10.54**	221.73**	191.17**
Error	70	8.43	211.01	15.25	0.63	0.17	4.00	21.09	23.85
Varience components									
σ^2GCA		58.57	968.92	76.47	0.40	0.14	9.60	15.54	7.97
σ^2SCA		182.32	5204.97	262.57	1.27	0.88	41.62	78.69	63.61
σ^2GCA/σ^2SCA		0.32	0.19	0.29	0.32	0.16	0.23	0.20	0.13
Predictability ratio (PR)		0.39	0.27	0.37	0.39	0.24	0.32	0.28	0.20
Narrow sense heritability (h_{ns})		0.76	0.53	0.71	0.60	0.42	0.59	0.48	0.31

*,** F probability significant at P 0.05 and 0.01, respectively. σ^2GCA, variance due to general combining ability; σ^2SCA, variance due to specific combining ability

3.2.2.1. Estimates of *gca*, *sca* and reciprocal effects of parents and hybrids

3.2.2.1.1. Estimates of general combining ability (*gca*) effects

Estimates of *gca* effects of parent ICMR 157001 exhibited positive and significant *gca* effects for panicle length. ICMR 157002 showed significant and positive gca effects for all the traits studied except for panicle circumference, grain yield and grain Zn content (Table 10). The parent ICMR 157005 exhibited positive and significant gca effects for panicle circumference. The *gca* effects of ICMR 157001, ICMR 157004 and ICMR 167011 is positive but not significant for grain yield. The gca effects of ICMR 157003 and ICMR 157004 are positives but not significant for grain Fe and Zn content.

Table 10. Estimates of general combining ability effects of agronomic and morphological traits of parents of pearl millet at Sadore.

Genotype/Traits	Days to 50% flowering	Plant height	Panicle length	Panicle circumference	Grain yield	Biomass yield	Grain Fe content	Grain Zn content
ICMR 157001	-1.06	6.08	5.02**	-0.59**	0.17	-0.03	-2.88*	-2.28
ICMR 157002	7.14**	26.63**	4.45**	-0.11	-0.09	2.76**	2.85*	2.10
ICMR 157003	-2.69*	-14.66**	-0.53	-0.01	-0.19	-1.35*	1.30	1.26
ICMR 157004	-2.31*	-3.30	-0.45	0.26	0.21	0.39	0.26	0.31
ICMR 157005	0.17	-10.37*	-5.95**	0.42*	-0.22*	-1.07*	-1.49	-0.82
ICMR 167011	-1.25	-4.38	-2.54*	0.03	0.12	-0.70	-0.04	-0.57
SE±	**0.76**	**3.83**	**1.03**	**0.21**	**0.11**	**0.53**	**1.21**	**1.29**

*, ** t test significant at P 0.05 and 0.01, respectively.

3.2.2.1.2. Estimates of specific combining ability (*sca*) effects

The estimates of sca effects of crosses for traits examined revealed that most of the crosses exhibited significant and positive *sca* effects (Table 11). The crosses ICMX 1770192, ICMX 1770198, and ICMX 1770209 exhibited significant and positive sca effects for days to 50% flowering, whereas ICMX 1770193, ICMX 1770194, ICMX 1770197, ICMX 1770204 and ICMX 1770208 exhibited significant negative sca effects. The crosses ICMX 1770192, ICMX 1770193, ICMX 1770198, ICMX 1770199, ICMX 1770203, and ICMX 1770209 exhibited significant and positive *sca* effects for plant height.

Good specific combiners for panicle length were ICMX 1770190, ICMX 1770194, ICMX 1770199, ICMX 1770202, ICMX 1770203, and ICMX 1770209 (Table 11). ICMX 1770197 and ICMX 1770214 showed positive and significant sca effects for panicle circumference. Significant positive sca effects by the crosses ICMX 1770192, ICMX 1770198, and ICMX 1770199 was recorded for biomass yield. Positive and significant sca effects for grain Fe and Zn contents were expressed by crosses ICMX 1770197, and ICMX 1770204.

3.2.2.1.3. Estimates of reciprocal effects

Estimates of reciprocal effects of the crosses for the traits examined showed that ICMX 1770201, ICMX 1770206, ICMX 1770207, and ICMX 1770217 exhibited significant negative reciprocal effects for days to 50% flowering (Table 11). ICMX 1770207, ICMX 1770212 and ICMX 1770213 exhibited significant and positive reciprocal effects for plant height. The crosses ICMX 1770200, ICMX 1770201, ICMX 1770206, and ICMX 1770210 exhibited significant negative reciprocal effects for grain yield. The cross ICMX 1770207 for biomass yield; ICMX 1770206 and ICMX 1770217 for grain Fe and Zn contents exhibited significant positive reciprocal effects.

Table 11. Estimates of specific and reciprocal combining ability effects of agronomic and morphological traits of F_1 crosses of pearl millet at Sadore.

Genotype/Traits	Days to 50% flowering	Plant height	Panicle length	Panicle circumference	Grain yield	Biomass yield	Grain Fe content	Grain Zn content
Direct crosses								
ICMX 1770190	2.39	10.52	5.79*	-0.28	-0.04	0.38	-2.20	-2.23
ICMX 1770191	-2.28	-1.69	0.32	0.17	0.08	0.28	1.25	1.71
ICMX 1770192	4.67**	27.56**	-1.82	0.47	0.26	2.79*	2.29	1.52
ICMX 1770193	-6.14**	17.19*	-0.27	0.52	0.41	0.10	2.99	1.73
ICMX 1770194	-5.22**	11.58	5.10*	-0.20	0.39	0.69	-2.46	-1.51
ICMX 1770196	-1.47	-20.79*	-1.21	0.41	0.24	-0.15	-1.85	0.18
ICMX 1770197	-13.86**	-52.93**	-9.96**	0.93*	-0.21	-5.68**	6.96*	8.02**
ICMX 1770198	3.17*	36.09**	3.21	-0.40	0.41	5.27**	-0.61	-2.14
ICMX 1770199	2.58	29.03**	5.35*	-0.35	0.31	2.95*	-1.33	-0.61
ICMX 1770202	2.81	-4.26	4.62*	-0.34	-0.09	-0.45	-3.50	-5.90*
ICMX 1770203	2.67	15.82*	9.46**	-0.34	0.40	0.79	-3.79	-3.33
ICMX 1770204	-5.58**	-25.18*	-13.84**	0.72	-0.58*	-1.80	10.44**	6.80*
ICMX 1770208	-3.39*	-25.65**	-6.29**	-0.48	-0.33	-1.60	0.23	0.76
ICMX 1770209	6.03**	24.12**	4.97*	-0.54	0.30	1.60	-3.29	-1.27
ICMX 1770214	-0.44	-3.75	-6.26*	0.96*	-0.45*	-2.03	-2.48	-3.05
SE±	**1.74**	**8.73**	**2.35**	**0.48**	**0.25**	**1.20**	**2.76**	**2.93**
Reciprocals								

ICMX 1770195	-0.67	3.22	0.56	-0.11	0.12	0.25	-1.60	0.52
ICMX 1770200	5.17*	-27.72**	-6.56*	-0.11	-0.70*	-2.05	4.53	4.02
ICMX 1770201	-5.17*	-47.06**	-4.22	-0.50	-0.61*	-5.56**	2.00	2.27
ICMX 1770205	5.50**	17.33	-2.17	0.33	-0.34	1.38	2.00	-2.35
ICMX 1770206	-5.17*	-48.94**	-14.56**	0.61	-1.02**	-2.75*	18.30**	16.70**
ICMX 1770207	-3.67*	44.89**	-0.61	0.89	0.46	2.50*	-0.65	-0.20
ICMX 1770210	1.50	-8.33	-6.00*	0.56	-0.51*	-1.20	2.88	-1.30
ICMX 1770211	0.33	7.00	0.78	0.44	-0.04	-1.05	-0.02	0.82
ICMX 1770212	-2.00	47.33**	1.06	0.94	0.50	1.94	-5.38	-3.88
ICMX 1770213	9.00**	23.33*	5.17*	-0.72	0.19	1.61	-5.00	-4.83
ICMX 1770215	1.33	5.72	-0.22	0.00	0.00	0.28	1.55	-0.70
ICMX 1770216	1.00	-2.94	4.44	-0.67	-0.11	-1.72	0.85	-2.62
ICMX 1770217	-10.33**	-30.11**	-2.06	-0.17	-0.42	-0.46	15.03**	9.42**
ICMX 1770218	-2.33	4.00	0.83	0.06	-0.09	-0.36	1.80	2.70
ICMX 1770219	2.33	-15.50	-5.67*	0.39	-0.23	-0.46	3.67	4.33
SE±	**2.05**	**10.27**	**2.76**	**0.56**	**0.29**	**1.41**	**3.25**	**3.45**

*, ** t test significant at P 0.05 and 0.01, respectively.

3.2.3. Mid parent and better parent heterosis

The degree and significance of mid-parent and better parent heterosis varied from cross to cross and from trait to trait for the traits examined (Table 12). Nine crosses exhibited significant positive mid parent heterosis (MPH) and better parent heterosis (BPH), while six crosses exhibited significant positive MPH for grain yield. The crosses ICMX 1770202, ICMX 1770206, and ICMX 1770217 exhibited significant negative MPH and BPH for grain yield. For biomass yield, six crosses showed significant positive heterosis simultaneously over MPH and BPH and seven crosses exhibited significant positive MPH. The crosses ICMX 1770206 and ICMX 1770217 had significant positive MPH and BPH for both grain Fe and Zn content. The cross ICMX 1770200 exhibited significant positive MPH for both grain Fe and Zn content. The crosses ICMX 1770205 and ICMX 1770192 had significant positive MPH for Fe and Zn respectively.

Table 12. Estimates of relative and better parents heterosis for agronomic and morphological traits of pearl millet at Sadore.

Genotype	Days to 50% flowering		Plant height		Panicle length		Panicle circumference		Grain yield		Biomass yield		Grain Fe content		Grain Zn content	
	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
Direct crosses																
ICMX 1770190	-4.82*	6.58*	21.43**	-4.70	26.87**	20.10**	4.68	-4.29	191.73**	146.51*	73.07**	1.20	2.03	-11.52	-1.58	-10.55
ICMX 1770191	-18.63**	-14.88**	24.15**	5.40	28.23**	26.10**	13.39*	4.34	218.36**	152.17**	130.11**	52.84	-2.82	-11.71	-5.71	-16.38
ICMX 1770192	-8.79**	-5.09	15.37**	-5.38	1.53	-5.72	6.57	-7.60	104.86**	30.32	33.03	-23.78	6.96	-0.40	18.94*	13.13
ICMX 1770193	-18.31**	-18.31**	57.92**	53.69**	30.37**	9.73	5.80	-8.75	427.34**	354.80**	371.75**	312.78**	-2.10	-11.69	1.74	-11.06
ICMX 1770194	-16.22**	-13.50**	39.56**	35.51**	19.21**	17.23*	6.26	-2.85	94.21**	27.22	148.89*	85.71	-7.01	-14.60	-0.11	-6.29
ICMX 1770196	-2.39	14.88**	4.13	-5.44	10.25	2.72	17.98**	17.14*	223.45**	126.91**	95.20**	47.96**	-4.71	-9.52	-1.97	-4.61
ICMX 1770197	-18.44**	-4.57	-8.12*	-13.19**	4.25	2.14	6.04	0.00	114.31**	27.29	-34.93*	-39.44**	-22.08**	-27.85**	-15.62	-19.58*
ICMX 1770198	-3.56	7.99**	26.73**	-2.47	10.94	-10.67	-6.67	-12.50*	316.05**	306.02**	187.49**	62.01**	-4.37	-8.51	-11.26	-15.02
ICMX 1770199	-4.31*	10.99**	26.07**	1.15	0.40	-6.45	10.00	10.00	84.38**	11.92	118.47**	46.83**	-2.86	-8.81	10.62	6.92
ICMX 1770202	4.08	4.62	-40.02**	-42.49**	1.55	-7.16	-10.82	-16.46*	-44.93*	-59.63**	-74.18**	-81.35**	-0.56	-3.18	-12.17	-18.43*
ICMX 1770203	0.99	5.65	-18.07**	-31.97**	24.24**	6.03	-10.07	-16.26*	27.42	-9.31	-20.04	-50.17	2.45	1.65	-6.88	-8.42
ICMX 1770204	2.27	3.58	2.76	-10.56*	-37.37**	-37.37**	19.42**	18.57*	-13.84	-34.06	-35.38	-46.13	-6.92	-8.03	-7.38	-12.80
ICMX 1770208	-23.90**	-20.82**	-25.79**	-40.41**	-42.65**	-54.53**	4.40	3.75	-33.27	-60.05**	-65.96**	-81.12**	11.53	7.76	11.23	1.73
ICMX 1770209	7.80**	8.62**	12.39*	-5.61	-5.74	-13.82*	-3.36	-8.86	21.75	14.33	15.61	-25.06	-8.20	-9.55	-6.56	-7.91
ICMX 1770214	-8.96**	-6.00*	35.64**	28.29**	-9.09	-22.42**	11.99*	4.99	-1.82	-39.88*	20.40	-17.57	-18.08*	-19.69*	-27.29**	-32.60**

Table 12. Estimates of relative and better parents heterosis for agronomic and morphological traits of pearl millet at Sadore.

Genotype	Days to 50% flowering		Plant height		Panicle length		Panicle circumference		Grain yield		Biomass yield		Grain Fe content		Grain Zn content	
	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
Reciprocals																
ICMX 1770195	-6.50**	4.69	24.84**	-2.02	29.49**	22.58**	1.56	-7.15	253.75**	198.91**	83.24**	7.14	-5.90	-18.40*	1.49	-7.76
ICMX 1770200	-3.43	1.03	-8.86	-22.63**	-5.10	-6.68	10.24	1.45	-7.73	-26.91	-10.73	-40.71	21.05**	9.97	17.46*	4.17
ICMX 1770201	-15.91**	-1.03	-38.58**	-44.23**	-9.98	-16.12*	5.03	4.28	3.27	-27.55	-77.52**	-82.96**	4.35	-0.92	9.94	6.99
ICMX 1770205	7.31**	11.66**	34.97**	10.70*	-8.46	-15.00*	15.33*	0.00	40.93	-10.34	81.76**	4.15	17.80*	9.69	4.19	-0.90
ICMX 1770206	-31.89**	-20.31**	-50.83**	-53.54**	-59.41**	-60.23**	20.80**	13.92*	-90.39**	-94.29**	-94.84**	-95.20**	62.88**	50.81**	79.17**	70.76**
ICMX 1770207	-7.14*	-6.66*	3.38	-0.88	-1.31	-9.77	10.81	3.79	30.33	-4.46	-4.09	-30.73*	-3.76	-6.29	-13.27	-19.45*
ICMX 1770210	-14.08**	-14.08**	45.58**	41.68**	-5.27	-20.28**	20.29**	3.75	168.10*	131.22*	181.51	146.32	12.95	1.88	-5.62	-17.50*
ICMX 1770211	-2.73	8.92**	34.23**	3.30	15.27*	-7.19	4.00	-2.50	288.27**	278.92**	143.62**	37.29*	-4.46	-8.60	-7.02	-10.97
ICMX 1770212	-4.90	-0.51	39.48**	15.81**	30.64**	11.48*	12.74*	4.99	205.56**	117.47**	121.88*	38.27	-23.09**	-23.69**	-26.44**	-27.65**
ICMX 1770213	2.44	6.59*	1.10	-18.81**	-14.70*	-32.38**	-11.95*	-12.50*	4.87	-37.22*	-7.02	-48.42**	-12.82	-15.76*	-14.94	-22.20*
ICMX 1770215	-12.36**	-9.51**	47.56**	43.29**	18.06**	16.10*	6.26	-2.85	95.14**	27.83	174.14**	104.55*	1.25	-7.00	-4.43	-10.35
ICMX 1770216	-1.73	13.99**	23.09**	-1.24	21.70**	13.40*	-7.15	-7.15	60.51*	-2.57	58.15*	6.30	1.03	-5.16	-4.02	-7.22
ICMX 1770217	-29.11**	-28.20**	-32.17**	-40.96**	-48.00**	-48.00**	15.11*	14.28*	-87.88**	-90.72**	-60.77	-67.30*	65.81**	63.83**	43.81**	35.40**
ICMX 1770218	0.76	1.52	16.80**	-1.90	-1.83	-10.24	-2.02	-7.60	10.86	4.10	4.45	-32.29*	0.75	-0.73	9.32	7.74
ICMX 1770219	-2.19	0.99	13.30*	7.16	-43.42**	-51.72**	21.33**	13.75*	-53.34	-71.43**	-25.19	-48.79	-0.47	-2.42	-4.14	-11.14

*, ** t test significant at P 0.05 and 0.01, respectively, MPH, mid parent heterosis; BPH, better parent heterosis.

3.2.4. Association of agronomic and morphological traits

Association of agronomic and morphological traits revealed presence of significant and positive (r = 0.93**) correlation of grain Fe content with grain Zn content (Table 13). Plant height (r = -0.43**; -0.48**), panicle length (r = -0.52**; -0.53**) and grain yield (r = -0.58**; -0.52**) exhibited significant negative correlation with grain Fe and Zn contents, respectively. Plant height (r = 0.66**; 0.89**) and panicle length (r = 0.65**; 0.63**) exhibited significant and positive correlation with grain yield and biomass yield.

Table 13. Association of agronomic and morphological traits of crosses of pearl millet restorers' lines at Sadore.

Traits	Days to 50% flowering	Plant height	Panicle length	Panicle circumference	Grain yield	Biomass yield	Grain Fe content	Grain Zn content
Days to 50% flowering	1.00							
Plant height	0.51**	1.00						
Panicle length	0.41**	0.67**	1.00					
Panicle circumference	-0.35*	-0.10	-0.63**	1.00				
Grain yield	0.00	0.66**	0.65**	-0.12	1.00			
Biomass yield	0.55**	0.89**	0.63**	-0.14	0.61**	1.00		
Grain Fe content	-0.31	-0.43**	-0.52**	0.30	-0.58**	-0.24	1.00	
Grain Zn content	-0.36*	-0.48**	-0.53**	0.32*	-0.52**	-0.29	0.93**	1.00

*,** Correlation coefficient significant at P 0.05 and 0.01 respectively.

3.3. Estimation of Standard Heterosis for Grain Yield and Grain Iron (Fe) and Zinc (Zn) Content in Single and Top Cross Hybrids of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) in.

3.3.1. Genetic variability and hybrids performance

Analysis of variance for individual (data not showed) as well as for pooled environment showed significant differences ($P \leq 0.01$ and $p \leq 0.05$) for all the traits among the locations, hybrids and the interaction of hybrid x location except for the variance of plant height and panicle circumference within locations, indicating presence of significant variability in the genotypes tested (Table 14). The variance due to location was higher than the variance due to hybrids for all the traits. Nevertheless, although the variation of location was higher than the variance of hybrids, it was not significant for plant height and panicle length, indicating their low contribution in the variance of the interaction, hybrid × location.

Table 14. Analysis of variance of pearl millet hybrids across Sadore, Gampela and Cinzana.

Source of variation	d.f.	Days to 50% flowering	Plant height	Panicle length	Panicle circumference	Grain yield	Grain Fe content	Grain Zn content
Replication	1	15.18	28.50	5.72	0.33	0.02	50.49	0.65
Location	2	5112.11*	60915.10^{NS}	1603.01*	39.93^{NS}	30.43*	3820.39**	3719.27**
Entry	111	75.70**	2401.70**	231.15**	4.65**	1.22**	280.16**	150.52**
Location x Entry	222	16.92**	503.50**	28.11**	0.97**	0.79**	43.06**	35.26**
Residual	333	9.45	260.90	15.91	0.71	0.05	14.67	17.08
Total	671							

*,** F probability significant at P 0.05 and 0.01, respectively; NS, non-significant F probability

Wide ranges were observed for all traits, based on the means for each hybrid for individual as well as across the three environments (Table 15). Also, according to the range of traits, Cinzana showed particular deviation for others location and across location, showed that the environment of Cinzana is different from others. This difference is very useful in the multilocation trial to evaluate the performance of genotypes.

The number of days to 50% flowering varied from 45 to 64 days in Sadore (Niger), form 45 to 63 days in Gampela (Burkina Faso), from 51 to 68 days in Cinzana (Mali) and form 49 to 63 days in the general mean of the three locations among the single cross hybrids whereas, it varied from 50 to 66 days, from 50 to 64 days, from 57 to 67 days and from 51 to 65 days respectively in Sadore, Gampela, Cinzana and across the three locations (Table 15).

Plant height varied fron 127.50 to 247.50 cm (Sadore), from 126.50 to 254.50 cm (Gampela), from 120 to 190 cm (Cinzana) and from 127.20 to 214 cm (across) among the single cross hybrids while it varied from 140 to 252.50 cm (Sadore), from 122.50 to 237.50 cm (Gampela), from 120 to 195 cm (Cinzana) and from 127.50 to 22.50 cm (across) among top cross hybrids (Table 15).

In Sadore, panicle length varied from 22.50 to 48 cm (SCH) and from 24.50 to 58.50 cm (TCH); in Gampela from 23.50 to 48.50 cm (SCH) and from 22.50 to 59.50 cm (TCH); in Cinzana form 19.50 to 50.50 cm (SCH) and from 25 to 52.50 cm (TCH); from 22.67 to 47.83 cm (SCH) and from 26.67 to 53.50 cm across the three locations (Table 15).

Panicle circumference ranged among single cross hybrids from 7 to 11.50 cm, from 7 to 12.50 cm, from 7 to 10 cm and from 7.17 to 10.83 cm respectively in Sadore, Gampela, Cinzana and across the three locations whereas for top cross hybrids, it ranged from 6.50 to 11 cm in Sadore, from 7 to 10 in Gampela, from 6 to 10.5 cm in Cinzana and from 7.17 to 10.50 cm across the three locations (Table 15).

Grain yield varied from 0.74 to 3.03 t/ha in Sadore, from 0.43 to 4.21 t/ha in Gampela, from 0.61 to 2.96 t/ha in Cinzana and from 0.92 to 2.73 across locations for the single cross hybrids, while it ranged from 0.97 to 3.21 t/ha, from 1.38 to 4.52 t/ha, from 0.60 to 3.12 t/ha and from 1.47 to 3.21 t/ha among the top cross hybrids in Sadore, Gampela, Cinzana and across the three locations respectively (Table 15).

Grain Fe and Zn varied from 28.25 to 67 mg/kg (Fe), 23.78 to 52.83 mg/k (ZN) from 34.63 to 82.10mg/kg (FE), 29.90 to 51.55mg/kg (Zn) from 35 to 71.73 mg/kg (Fe), 31.97 to 58.57 mg/kg (Zn) and from 37.75 to 73.61 mg/kg, 31.57 to 52.33 mg/kg for single cross hybrids respectively in Sadore, Gampela, Cinzana and across thr three locations (Table 15). Whereas, in top cross hybrids Fe and Zn ranged from 27.23 to 54.55 mg/kg (Fe), 23.33 to 52.83 mg/kg (Zn) in Sadore; from 32.85 to 61.98 mg/kg (Fe), 30.50 to 52.85 mg/kg (Zn) in Gampela; from 36 to 68.85 mg/kg (Fe), 30.75 to 58.90 mg/kg (Zn) in Cinzana and from 37.16 to 59.12 mg/kg (Fe), 31.57 to 53.26 mg/kg (Zn) in the general mean of the three locations.

The overall mean among single cross hybrids in all the location as well as across the three location showed some earliness over top cross hybrids for number of days to 50% flowering, panicle circumference and more grain Fe and Zn content whereas the top cross hybrids had some superiority regarding plant height, panicle length and grain yield (Table 15). For example across the location, the overall mean for number of days to 50% flowering for single cross hybrids was 55.62 days against 58.58 days for top cross hybrids, for panicle circumference 8.90 cm (SCH) against 8.44 cm (TCH); 47.05 mg/kg and 39.44 mg/kg for single cross hybrids against 43.19 mg/kg and 37.66 mg/kg for top cross hybrids respectively for grain Fe and Zn content. While, the top cross hybrids had 190.92 cm against 181.53 cm for single cross hybrids; for panicle length 39.15 cm (TCH) against 33.5 cm (SCH) and 2.03 t/ha (TCH) against 1.65 t/ha (SCH).

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
Single cross hybrids																
ICMH 1201	46.00	45.00	54.50	48.50	173.50	151.50	147.50	157.50	28.00	24.50	22.50	25.00	10.00	11.00	10.00	10.33
ICMH 1301	52.00	46.50	50.50	49.67	155.50	173.00	150.00	159.50	22.50	23.50	22.00	22.67	10.00	12.00	10.00	10.67
ICMH 157222	56.00	54.00	61.00	57.00	147.50	155.50	127.50	143.50	44.50	48.50	50.50	47.83	8.50	8.50	7.50	8.17
ICMH 177002	51.50	51.00	60.50	54.33	139.00	139.00	137.50	138.50	47.00	40.00	33.50	40.17	8.00	8.50	7.00	7.83
ICMH 177022	56.50	58.00	67.00	60.50	223.00	226.50	165.00	204.80	39.00	41.50	33.50	38.00	8.50	9.00	7.50	8.33
ICMH 177111	59.00	58.00	61.00	59.33	244.00	190.50	190.00	208.20	43.00	39.00	33.50	38.50	8.50	8.00	8.50	8.33
ICMX 1871003	51.50	53.00	62.50	55.67	136.50	141.00	122.50	133.30	36.00	35.00	31.00	34.00	8.50	8.00	7.50	8.00
ICMX 1871018	63.50	57.00	67.50	62.67	127.50	126.50	127.50	127.20	34.50	34.00	36.00	34.83	7.00	7.50	7.50	7.33
ICMX 1871023	55.50	57.00	62.00	58.17	151.00	185.00	155.00	163.70	42.00	39.50	30.50	37.33	8.00	7.00	7.00	7.33
ICMX 1871027	48.00	47.50	60.50	52.00	184.50	188.50	160.00	177.70	48.00	37.00	30.50	38.50	8.00	8.00	7.50	7.83
ICMX 1871032	51.00	51.00	61.00	54.33	152.50	127.50	120.00	133.30	35.50	33.00	33.00	33.83	7.50	8.00	8.50	8.00
ICMX 1871037	45.50	46.50	58.50	50.17	247.50	200.00	185.00	210.80	39.50	46.00	29.50	38.33	9.00	10.50	9.00	9.50
ICMX 1871048	48.00	50.00	60.00	52.67	180.00	192.00	165.00	179.00	31.50	39.00	29.50	33.33	10.00	9.50	8.50	9.33
ICMX 1871049	53.00	54.00	60.00	55.67	196.00	181.00	182.50	186.50	33.50	28.00	40.50	34.00	9.00	8.00	10.00	9.00

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 1871050	49.50	51.50	60.50	53.83	170.00	147.50	157.50	158.30	35.50	34.50	28.00	32.67	11.50	10.50	8.00	10.00
ICMX 187760	48.00	49.00	63.50	53.50	178.00	150.50	157.50	162.00	32.50	31.00	28.00	30.50	10.00	8.50	8.00	8.83
ICMX 187762	46.50	52.00	60.50	53.00	192.00	195.00	145.00	177.30	31.00	31.50	25.00	29.17	10.50	11.00	9.50	10.33
ICMX 187763	49.50	55.00	58.00	54.17	190.50	145.00	160.00	165.20	32.50	31.00	28.50	30.67	9.00	9.00	9.00	9.00
ICMX 187765	48.00	51.00	63.00	54.00	150.00	176.00	136.00	154.00	27.50	27.00	23.50	26.00	9.50	9.50	8.50	9.17
ICMX 187766	46.50	50.50	59.00	52.00	227.50	184.50	178.50	196.80	36.50	31.00	31.00	32.83	9.00	9.00	9.00	9.00
ICMX 187769	51.00	61.50	67.00	59.83	204.50	157.50	187.50	183.20	27.50	31.50	29.00	29.33	9.50	8.00	8.50	8.67
ICMX 187772	53.00	53.50	61.00	55.83	195.00	148.00	150.00	164.30	24.00	24.50	21.00	23.17	10.50	10.50	10.00	10.33
ICMX 187773	50.00	50.50	61.00	53.83	202.50	186.00	157.50	182.00	29.50	29.00	28.00	28.83	10.50	9.50	9.00	9.67
ICMX 187775	47.50	52.00	58.00	52.50	221.00	168.50	170.00	186.50	32.50	25.50	28.00	28.67	9.50	9.50	9.00	9.33
ICMX 187778	46.00	52.50	60.00	52.83	208.00	222.50	162.50	197.70	30.50	30.50	29.00	30.00	8.00	9.00	8.50	8.50
ICMX 187781	46.50	48.00	62.00	52.17	207.00	135.00	167.50	169.80	37.00	29.50	29.00	31.83	10.00	7.50	9.00	8.83
ICMX 187786	48.50	46.00	61.00	51.83	225.00	183.00	167.50	191.80	34.50	36.00	28.50	33.00	8.50	8.00	8.50	8.33
ICMX 187788	47.00	45.50	58.00	50.17	226.50	201.50	160.00	196.00	29.50	27.00	19.50	25.33	10.00	12.50	10.00	10.83
ICMX 187803	51.50	55.00	65.00	57.17	206.00	197.50	160.00	187.80	41.00	39.50	31.00	37.17	9.00	9.00	8.00	8.67
ICMX 187806	58.00	57.00	65.00	60.00	206.50	204.50	165.00	192.00	38.00	39.50	31.50	36.33	10.00	10.50	8.00	9.50

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187807	47.50	48.50	60.50	52.17	224.00	189.50	175.00	196.20	44.50	42.50	33.00	40.00	7.50	8.50	7.50	7.83
ICMX 187808	53.00	56.00	65.50	58.17	196.50	153.00	179.00	176.20	39.00	36.00	33.00	36.00	8.00	8.50	8.00	8.17
ICMX 187826	51.00	51.00	58.50	53.50	161.00	165.00	132.50	152.80	43.50	40.00	32.50	38.67	8.50	8.50	8.00	8.33
ICMX 187827	53.00	52.00	62.00	55.67	226.00	208.00	162.50	198.80	28.00	28.00	27.50	27.83	10.50	11.50	9.50	10.50
ICMX 187829	56.50	53.50	65.00	58.33	190.00	210.00	170.00	190.00	27.00	27.50	24.00	26.17	11.00	12.00	9.50	10.83
ICMX 187830	51.00	53.50	60.00	54.83	235.50	234.00	172.50	214.00	34.00	36.50	29.50	33.33	10.00	9.50	8.50	9.33
ICMX 187832	53.00	51.50	63.00	55.83	219.00	237.50	180.00	212.20	34.50	30.00	32.50	32.33	10.00	11.00	8.50	9.83
ICMX 187853	53.00	53.50	62.00	56.17	225.00	215.00	160.00	200.00	32.00	33.50	30.00	31.83	8.50	9.00	8.00	8.50
ICMX 187854	53.50	54.00	61.00	56.17	192.00	193.50	167.50	184.30	31.50	32.00	29.00	30.83	10.00	10.00	8.00	9.33
ICMX 187856	55.50	54.00	65.50	58.33	203.00	193.00	142.50	179.50	33.00	30.00	24.50	29.17	11.00	11.00	9.00	10.33
ICMX 187857	51.00	48.00	62.00	53.67	181.50	145.00	162.50	163.00	34.50	32.50	33.50	33.50	8.00	8.50	7.50	8.00
ICMX 187859	48.50	50.50	65.50	54.83	192.50	168.00	175.00	178.50	33.50	37.50	28.50	33.17	8.00	10.00	8.50	8.83
ICMX 187860	48.00	53.00	63.50	54.83	200.50	194.50	156.00	183.70	40.50	33.00	34.50	36.00	9.00	8.50	7.50	8.33
ICMX 187861	44.50	56.00	59.00	53.17	182.50	173.00	155.00	170.20	30.00	26.00	27.00	27.67	10.00	10.00	9.50	9.83
ICMX 187862	55.50	58.00	61.00	58.17	201.50	192.50	170.00	188.00	34.00	35.50	30.50	33.33	8.00	10.00	8.50	8.83
ICMX 187864	62.00	55.00	64.00	60.33	214.00	222.00	162.50	199.50	32.50	35.50	28.50	32.17	9.50	9.50	8.00	9.00

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187865	49.00	53.50	62.00	54.83	217.50	199.50	156.00	191.00	39.50	37.00	33.00	36.50	7.50	7.00	7.00	7.17
ICMX 187867	52.50	53.50	64.00	56.67	191.00	216.00	185.00	197.30	36.00	35.50	31.00	34.17	8.00	9.00	7.50	8.17
ICMX 187868	47.00	52.00	63.00	54.00	205.00	164.50	167.50	179.00	28.00	33.50	28.50	30.00	9.50	9.50	8.50	9.17
ICMX 187870	54.50	53.00	65.00	57.50	215.50	212.50	175.00	201.00	35.00	32.50	33.00	33.50	9.50	10.50	9.50	9.83
ICMX 187872	56.00	62.00	65.50	61.17	218.50	190.00	165.00	191.20	35.50	38.50	30.50	34.83	9.50	10.00	9.00	9.50
ICMX 187875	53.00	53.50	66.00	57.50	230.00	146.00	180.00	185.30	42.00	43.00	34.00	39.67	7.00	8.00	8.50	7.83
ICMX 187876	49.00	58.00	60.00	55.67	218.00	228.00	187.50	211.20	31.50	38.00	30.50	33.33	8.00	11.00	8.00	9.00
ICMX 187877	61.00	57.50	61.50	60.00	211.50	208.50	187.50	202.50	31.50	33.00	29.50	31.33	9.50	11.00	7.50	9.33
ICMX 187878	49.00	52.00	59.00	53.33	220.50	179.50	170.00	190.00	39.50	35.50	27.00	34.00	7.50	7.50	7.00	7.33
ICMX 187880	47.50	55.00	59.50	54.00	220.50	196.00	167.50	194.70	39.50	40.00	33.00	37.50	8.50	8.00	8.00	8.17
ICMX 187881	47.00	55.50	63.50	55.33	217.00	192.00	170.00	193.00	45.00	39.00	43.00	42.33	8.50	8.00	7.50	8.00
ICMX 187882	49.50	44.00	59.00	50.83	177.00	205.00	167.50	183.20	32.00	33.00	28.50	31.17	8.50	9.50	8.50	8.83
ICMX 187883	56.50	57.50	65.50	59.83	225.00	195.50	175.00	198.50	36.50	35.50	31.50	34.50	9.50	10.50	8.50	9.50
ICMX 187885	58.00	58.50	68.00	61.50	206.00	254.50	162.50	207.70	34.00	32.00	28.50	31.50	8.50	10.50	7.50	8.83
ICMX 187889	59.50	54.50	66.50	60.17	197.50	217.50	180.00	198.30	35.50	40.00	38.50	38.00	8.00	9.50	9.00	8.83
ICMX 187891	55.50	55.50	63.00	58.00	223.50	193.00	177.50	198.00	37.00	27.50	31.00	31.83	8.50	10.50	8.50	9.17

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187892	58.00	63.00	63.00	61.33	198.50	172.50	168.50	179.80	33.50	29.00	27.50	30.00	10.50	9.50	7.00	9.00
ICMX 187893	54.00	50.00	62.00	55.33	199.00	196.50	160.00	185.20	38.00	37.00	30.00	35.00	10.00	9.00	8.00	9.00
ICMX 187895	48.00	54.50	64.00	55.50	217.50	189.00	175.00	193.80	41.00	39.50	31.50	37.33	10.00	10.00	8.00	9.33
ICMX 187897	49.50	50.50	59.00	53.00	201.00	194.50	165.00	186.80	30.50	34.00	27.00	30.50	9.00	10.00	8.50	9.17
ICMX 187989	51.00	48.50	64.00	54.50	151.50	162.50	132.50	148.80	43.00	37.50	31.00	37.17	8.00	8.00	7.00	7.67
ICMX 187995	58.50	56.50	67.00	60.67	140.50	170.50	147.50	152.80	41.50	43.00	35.00	39.83	7.50	8.00	7.00	7.50
Top cross hybrids																
ICMH 177016	57.50	58.50	62.50	59.50	252.50	190.50	180.00	207.70	47.50	47.50	34.00	43.00	9.00	9.50	8.00	8.83
ICMH 177017	54.50	61.00	62.00	59.17	228.00	237.50	175.00	213.50	38.00	53.00	35.50	42.17	10.00	8.50	8.50	9.00
ICMH 177018	61.00	57.00	62.50	60.17	197.50	220.00	195.00	204.20	36.00	44.00	28.50	36.17	9.00	9.00	8.50	8.83
ICMH 177019	55.50	50.00	60.50	55.33	195.50	199.00	170.00	188.20	34.00	33.00	35.50	34.17	9.50	10.00	9.50	9.67
ICMH 177020	59.00	57.00	66.50	60.83	207.50	181.50	185.00	191.30	39.50	43.50	36.50	39.83	9.50	9.00	7.50	8.67
ICMH 177023	61.50	60.00	58.00	59.83	185.00	184.00	170.00	179.70	32.50	37.50	30.50	33.50	9.50	9.50	9.50	9.50
ICMH IS 16027	59.00	54.50	63.00	58.83	202.50	223.50	195.00	207.00	42.00	51.50	40.50	44.67	7.00	8.50	7.50	7.67
ICMH IS 16037	62.50	57.00	67.00	62.17	217.50	166.00	180.00	187.80	52.00	45.50	46.00	47.83	8.00	8.00	7.00	7.67
ICMH IS 16038	52.50	56.00	64.50	57.67	222.00	212.00	180.00	204.70	55.00	48.00	39.50	47.50	7.00	7.50	7.50	7.33

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMH IS 16040	62.50	56.50	66.00	61.67	213.50	217.00	185.00	205.20	38.00	41.00	31.00	36.67	9.50	9.00	7.50	8.67
ICMH IS 16044	58.00	52.50	56.50	55.67	217.50	207.00	167.50	197.30	50.00	41.50	30.00	40.50	8.00	8.00	7.00	7.67
ICMH IS 16052	54.00	54.50	64.50	57.67	190.00	167.50	165.00	174.20	48.50	43.50	42.50	44.83	8.50	7.50	7.00	7.67
ICMH IS 16075	62.50	60.00	62.50	61.67	204.00	204.50	187.50	198.70	31.00	40.00	34.50	35.17	9.00	8.50	8.50	8.67
ICMH IS 16076	65.00	57.50	61.50	61.33	217.50	220.00	180.00	205.80	45.00	55.00	38.50	46.17	8.00	8.50	7.50	8.00
ICMH IS 16120	61.50	58.00	63.00	60.83	204.50	203.50	195.00	201.00	40.00	43.00	38.50	40.50	7.50	8.00	8.00	7.83
ICMH IS 16187	62.00	60.50	67.00	63.17	194.00	202.00	180.00	192.00	43.00	45.50	42.00	43.50	7.50	8.50	8.00	8.00
ICMH IS 16214	60.00	58.00	65.50	61.17	200.00	217.50	172.50	196.70	44.00	43.50	42.50	43.33	8.50	9.50	7.50	8.50
ICMX 187001	50.50	52.50	60.00	54.33	205.00	173.50	175.00	184.50	34.50	39.00	34.00	35.83	9.00	9.00	8.50	8.83
ICMX 187011	57.00	60.00	66.00	61.00	227.50	175.00	165.00	189.20	36.00	38.50	40.00	38.17	9.50	9.50	10.00	9.67
ICMX 187018	62.50	62.00	62.50	62.33	193.80	198.50	165.50	185.90	36.00	32.50	25.00	31.17	7.50	8.50	8.50	8.17
ICMX 187020	65.00	63.50	66.00	64.83	207.00	198.50	177.50	194.30	40.00	48.00	52.50	46.83	6.50	8.50	7.50	7.50
ICMX 187023	58.00	54.00	61.00	57.67	205.00	180.50	190.00	191.80	37.50	45.00	33.50	38.67	8.00	8.00	7.50	7.83
ICMX 187026	48.50	47.00	58.00	51.17	169.50	165.00	170.00	168.20	30.00	26.00	31.50	29.17	8.00	8.00	10.00	8.67
ICMX 187031	53.50	57.50	62.00	57.67	215.00	188.50	162.50	188.70	29.50	31.50	28.50	29.83	9.00	10.00	9.50	9.50
ICMX 187040	56.00	54.50	62.50	57.67	205.00	201.50	180.00	195.50	40.50	42.00	35.00	39.17	7.50	7.50	7.00	7.33

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187041	51.00	50.00	60.50	53.83	167.50	162.50	152.50	160.80	27.00	28.50	32.50	29.33	10.50	10.00	9.50	10.00
ICMX 187042	54.50	56.50	61.50	57.50	204.00	153.00	182.50	179.80	37.50	44.00	40.00	40.50	8.00	8.50	7.00	7.83
ICMX 187046	49.00	52.50	60.00	53.83	176.00	152.00	162.50	163.50	28.00	26.50	30.50	28.33	8.50	9.50	9.00	9.00
ICMX 187048	55.00	50.50	63.50	56.33	220.00	196.50	170.00	195.50	50.00	46.00	35.50	43.83	8.50	9.00	7.50	8.33
ICMX 187050	65.50	57.00	64.50	62.33	210.00	150.00	175.00	178.30	39.00	43.50	34.50	39.00	9.00	8.50	7.50	8.33
ICMX 187054	55.50	57.50	61.00	58.00	188.00	195.00	170.00	184.30	41.50	50.00	45.00	45.50	9.50	8.00	7.50	8.33
ICMX 187068	51.00	50.00	60.00	53.67	207.50	189.00	170.00	188.80	34.00	34.50	33.00	33.83	8.00	8.50	8.50	8.33
ICMX 1871038	60.00	55.00	58.50	57.83	194.50	199.50	165.00	186.30	39.00	40.00	28.50	35.83	8.50	8.50	8.50	8.50
ICMX 1871039	56.50	57.00	61.50	58.33	205.00	216.50	182.50	201.30	52.50	44.50	40.00	45.67	7.50	7.00	8.50	7.67
ICMX 1871040	58.50	57.50	64.00	60.00	197.50	188.50	192.50	192.80	46.00	48.00	44.00	46.00	7.50	7.50	8.00	7.67
ICMX 1871041	58.50	55.50	68.00	60.67	215.50	213.00	180.00	202.80	57.50	52.50	38.00	49.33	8.50	7.00	6.00	7.17
ICMX 1871042	56.50	54.50	63.00	58.00	207.50	230.00	175.00	204.20	37.00	43.50	38.00	39.50	9.50	10.50	8.50	9.50
ICMX 1871043	56.50	54.00	64.50	58.33	210.50	205.00	177.50	197.70	36.50	43.50	34.00	38.00	8.00	9.50	7.50	8.33
ICMX 1871044	57.50	58.50	64.50	60.17	217.50	182.00	187.50	195.70	30.00	40.50	28.00	32.83	7.50	9.00	9.00	8.50
ICMX 1871045	47.50	52.50	64.00	54.67	140.00	122.50	120.00	127.50	25.50	22.50	32.00	26.67	10.00	9.50	8.00	9.17
ICMX 187572	48.00	55.00	63.50	55.50	250.00	226.50	185.00	220.50	58.50	59.50	42.50	53.50	8.50	7.00	7.50	7.67

Table 15. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Days to 50% flowering				Plant height (cm)				Panicle length (cm)				Panicle circumference (cm)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187848	58.50	53.00	62.00	57.83	193.50	191.00	172.50	185.70	24.50	33.50	26.50	28.17	11.00	10.00	10.50	10.50
Chakti (C1)	45.00	46.50	52.50	48.00	163.00	143.00	155.00	153.70	26.00	19.50	20.50	22.00	8.50	9.50	9.50	9.17
ICMV 167005 (C2)	64.00	58.00	65.50	62.50	265.00	241.50	182.50	229.70	47.50	39.50	34.00	40.33	9.50	9.00	8.50	9.00
Fpr	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Vr	**6.21**	**3.08**	**2.32**	**8.01**	**4.93**	**4.07**	**3.98**	**9.21**	**7.39**	**5.16**	**6.00**	**14.53**	**2.49**	**3.60**	**3.33**	**6.52**
Mean	**53.86**	**54.07**	**62.24**	**56.72**	**200.21**	**187.93**	**167.56**	**185.23**	**36.96**	**37.10**	**32.40**	**35.49**	**8.84**	**9.08**	**8.26**	**8.73**
SE±	**2.14**	**2.35**	**2.03**	**1.26**	**11.74**	**13.67**	**8.18**	**6.59**	**2.64**	**3.33**	**2.41**	**1.63**	**0.67**	**0.62**	**0.49**	**0.35**
LSD	**5.98**	**6.58**	**5.68**	**3.49**	**32.88**	**38.29**	**22.93**	**18.35**	**7.41**	**9.32**	**6.76**	**4.53**	**1.87**	**1.74**	**1.37**	**0.96**
CV (%)	**5.60**	**6.10**	**4.60**	**5.40**	**8.30**	**10.30**	**6.90**	**8.70**	**10.10**	**12.70**	**10.50**	**11.20**	**10.70**	**9.70**	**8.40**	**9.70**

C1, Check 1; C2, Check 2

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
Single cross hybrids												
ICMH 1201	2.09	0.88	0.84	1.27	62.50	68.65	62.13	64.42	57.03	41.37	58.57	52.33
ICMH 1301	1.13	1.03	1.19	1.12	67.00	82.10	71.73	73.61	50.15	47.47	53.00	50.21
ICMH 157222	1.83	1.20	1.29	1.44	38.05	44.95	40.20	41.07	34.95	36.90	36.00	35.95
ICMH 177002	1.20	0.90	1.21	1.10	33.25	36.00	35.00	34.75	31.70	31.81	32.35	31.95
ICMH 177022	2.28	1.48	1.18	1.65	41.25	50.03	46.20	45.82	35.00	47.85	39.30	40.72
ICMH 177111	2.63	1.45	1.01	1.70	44.70	45.50	47.05	45.75	34.70	43.45	37.52	38.56
ICMX 1871003	1.92	1.56	1.66	1.71	35.10	46.13	50.73	43.98	29.28	42.20	40.85	37.44
ICMX 1871018	1.30	1.53	0.79	1.20	28.25	43.98	40.83	37.68	23.95	38.92	37.90	33.59
ICMX 1871023	1.27	1.21	1.69	1.39	35.93	43.05	51.93	43.63	32.90	39.92	46.80	39.88
ICMX 1871027	1.27	0.82	1.12	1.07	37.85	49.30	44.38	43.84	29.93	46.85	39.27	38.68
ICMX 1871032	1.57	0.94	1.59	1.37	37.67	50.95	50.93	46.52	32.10	48.67	47.27	42.68
ICMX 1871037	2.15	1.77	1.15	1.69	51.03	54.15	59.65	54.94	42.18	48.12	50.10	46.80
ICMX 1871048	0.84	1.57	1.24	1.22	54.73	68.38	46.85	56.65	49.23	44.85	41.07	45.05
ICMX 1871049	2.61	0.82	2.96	2.13	40.60	52.95	57.08	50.21	36.93	43.80	53.07	44.60

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 1871050	2.22	0.75	2.80	1.92	63.77	66.90	57.70	62.79	49.18	47.55	46.82	47.85
ICMX 187760	1.12	0.78	1.18	1.03	41.65	50.25	45.33	45.74	36.80	45.50	42.05	41.45
ICMX 187762	1.50	1.64	1.79	1.64	46.05	44.93	55.13	48.70	31.95	42.20	38.32	37.49
ICMX 187763	2.15	0.77	1.69	1.54	42.98	50.58	54.23	49.26	33.18	48.70	45.05	42.31
ICMX 187765	0.74	1.54	1.23	1.17	51.80	53.25	58.88	54.64	43.58	44.80	52.87	47.08
ICMX 187766	2.20	1.38	1.45	1.68	45.48	47.10	57.85	50.14	38.93	46.30	44.62	43.28
ICMX 187769	1.90	1.71	1.33	1.65	41.68	68.88	61.95	57.50	35.48	49.77	46.70	43.98
ICMX 187772	1.12	0.87	0.94	0.98	51.28	54.93	58.08	54.76	45.70	47.40	49.60	47.57
ICMX 187773	2.87	1.57	1.36	1.93	37.43	49.73	49.73	45.62	35.08	29.90	43.52	36.17
ICMX 187775	1.91	1.62	1.56	1.70	38.68	58.40	42.93	46.67	34.58	42.70	40.77	39.35
ICMX 187778	1.69	1.33	1.98	1.67	34.88	52.90	44.23	44.00	34.08	40.17	40.45	38.23
ICMX 187781	1.17	1.22	1.29	1.23	48.35	65.48	62.48	58.77	43.25	44.85	46.35	44.82
ICMX 187786	1.39	1.42	1.12	1.31	41.73	66.15	52.95	53.61	40.48	40.75	46.22	42.48
ICMX 187788	1.06	1.81	1.93	1.60	40.05	51.50	50.88	47.47	34.58	41.65	39.97	38.73
ICMX 187803	2.57	1.07	0.61	1.42	40.30	39.95	57.45	45.90	32.78	35.80	43.12	37.23
ICMX 187806	2.22	2.16	1.94	2.11	38.98	45.45	47.33	43.92	24.38	43.12	35.37	34.29

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187807	3.03	1.39	1.17	1.86	36.90	43.80	46.23	42.31	31.40	40.75	39.05	37.07
ICMX 187808	1.50	0.62	0.97	1.03	34.45	41.43	41.20	39.02	24.98	33.02	38.55	32.18
ICMX 187826	1.87	0.93	1.94	1.58	31.10	42.40	38.88	37.46	25.18	38.10	34.32	32.53
ICMX 187827	2.89	3.08	1.75	2.57	39.78	46.83	51.18	45.92	31.33	43.97	39.95	38.42
ICMX 187829	2.05	3.48	1.80	2.44	45.15	39.35	46.50	43.67	32.80	34.60	34.55	33.98
ICMX 187830	3.03	3.40	1.77	2.73	38.45	50.90	50.00	46.45	33.58	48.22	33.97	38.59
ICMX 187832	2.10	2.56	1.00	1.89	34.80	36.75	42.63	38.06	29.88	34.50	37.10	33.83
ICMX 187853	3.26	1.76	1.47	2.16	38.33	41.20	47.68	42.40	33.88	35.87	39.57	36.44
ICMX 187854	1.88	2.35	1.26	1.83	36.48	39.20	47.05	40.91	29.75	32.07	43.17	35.00
ICMX 187856	2.10	3.86	1.55	2.50	47.15	43.15	53.43	47.91	37.55	39.75	40.20	39.17
ICMX 187857	2.05	1.26	0.92	1.41	40.35	44.40	47.18	43.97	28.45	43.20	42.72	38.13
ICMX 187859	1.53	0.56	0.67	0.92	35.90	42.70	44.90	41.17	31.48	39.40	42.05	37.64
ICMX 187860	2.07	1.44	1.39	1.64	41.30	46.10	39.58	42.32	39.38	42.50	37.87	39.92
ICMX 187861	1.91	1.15	1.32	1.46	46.30	51.60	51.25	49.72	33.60	43.85	42.80	40.08
ICMX 187862	2.04	1.41	1.34	1.60	41.85	45.83	51.85	46.51	41.60	37.87	41.05	40.18
ICMX 187864	2.07	2.81	0.92	1.93	33.83	43.85	52.10	43.26	31.55	41.77	41.45	38.26

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187865	2.28	1.28	0.94	1.50	39.73	47.88	54.40	47.33	32.35	46.62	42.10	40.36
ICMX 187867	2.40	1.24	0.82	1.49	36.18	42.55	43.90	40.87	25.30	38.45	36.40	33.38
ICMX 187868	1.55	1.51	1.07	1.38	50.12	53.80	56.83	53.58	44.23	42.55	47.00	44.59
ICMX 187870	1.85	1.76	1.28	1.63	48.30	52.48	55.58	52.12	39.53	44.45	55.42	46.47
ICMX 187872	2.42	3.39	1.25	2.36	37.70	43.20	45.45	42.12	33.78	41.40	41.47	38.88
ICMX 187875	2.27	1.32	2.21	1.93	35.55	42.83	48.60	42.32	27.93	34.80	31.97	31.57
ICMX 187876	2.00	2.19	0.81	1.67	44.40	43.73	47.25	45.12	33.08	33.95	40.32	35.78
ICMX 187877	1.41	2.63	1.23	1.76	40.83	36.70	44.98	40.83	33.20	34.35	40.60	36.05
ICMX 187878	1.66	1.67	1.54	1.62	46.05	46.23	48.40	46.89	37.03	37.15	41.82	38.67
ICMX 187880	1.46	0.43	1.29	1.06	36.68	42.60	41.53	40.27	34.38	40.32	39.55	38.08
ICMX 187881	2.09	1.61	1.11	1.61	39.58	40.20	45.85	41.87	34.85	35.80	44.65	38.43
ICMX 187882	1.27	1.47	1.27	1.34	42.62	44.23	42.55	43.13	38.38	39.90	41.35	39.88
ICMX 187883	2.86	1.95	0.73	1.84	44.33	47.83	46.73	46.29	33.50	45.47	41.87	40.28
ICMX 187885	2.75	3.01	1.08	2.28	43.02	52.98	45.63	47.21	23.78	50.90	39.42	38.03
ICMX 187889	2.04	4.21	1.86	2.70	35.95	34.63	36.93	35.83	29.15	45.35	33.85	36.12
ICMX 187891	2.16	1.53	2.24	1.98	50.05	64.75	54.43	56.41	34.18	35.12	36.32	35.21

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187892	2.53	2.88	1.71	2.37	50.08	51.33	55.60	52.33	32.35	43.75	41.85	39.32
ICMX 187893	1.53	0.96	0.98	1.15	49.65	42.98	48.23	46.95	34.78	37.67	38.27	36.91
ICMX 187895	3.03	1.31	0.92	1.75	45.20	51.48	51.70	49.46	42.98	45.25	44.55	44.26
ICMX 187897	1.96	2.19	2.02	2.06	48.28	66.00	50.65	54.97	32.30	44.00	45.15	40.48
ICMX 187989	1.26	1.14	1.05	1.15	36.58	54.00	57.18	49.25	28.73	51.55	45.40	41.89
ICMX 187995	2.35	1.44	1.09	1.63	34.12	47.60	41.08	40.93	28.08	41.00	37.20	35.43
Top cross hybrids												
ICMH 177016	1.86	3.70	1.23	2.26	47.05	47.73	50.83	48.53	38.30	45.37	47.00	43.56
ICMH 177017	2.03	3.58	2.35	2.65	44.55	54.85	39.88	46.42	42.18	47.92	35.22	41.78
ICMH 177018	1.92	3.01	1.28	2.07	31.60	48.20	48.55	42.78	27.73	44.00	43.65	38.46
ICMH 177019	1.31	2.75	1.82	1.96	45.80	50.08	52.68	49.52	33.58	44.62	45.35	41.18
ICMH 177020	1.73	2.50	1.57	1.93	42.12	46.30	52.98	47.13	34.35	48.60	43.57	42.18
ICMH 177023	1.47	3.47	0.95	1.96	33.43	44.83	55.85	44.70	28.60	43.90	46.37	39.63
ICMH IS 16027	1.52	2.46	0.99	1.66	37.85	45.08	40.95	41.29	32.93	37.05	34.30	34.76
ICMH IS 16037	2.34	1.59	0.60	1.51	37.35	39.63	41.05	39.34	29.23	35.60	33.50	32.78
ICMH IS 16038	2.04	2.44	1.40	1.96	40.95	40.90	36.00	39.28	33.88	30.75	30.75	31.79

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMH IS 16040	2.74	2.85	0.69	2.09	38.25	33.02	42.33	37.86	34.48	30.50	36.10	33.69
ICMH IS 16044	1.76	3.85	1.79	2.47	33.33	47.45	41.00	40.59	30.25	40.65	37.65	36.18
ICMH IS 16052	3.04	2.55	1.44	2.34	38.85	43.75	37.50	40.03	35.73	41.87	32.50	36.70
ICMH IS 16075	2.11	2.74	1.13	1.99	35.83	40.83	45.05	40.57	31.50	38.55	40.87	36.98
ICMH IS 16076	2.05	3.46	1.09	2.20	34.80	43.75	43.50	40.68	32.00	36.50	34.00	34.17
ICMH IS 16120	2.11	1.66	1.17	1.65	34.40	47.50	51.83	44.57	32.00	43.82	44.30	40.04
ICMH IS 16187	1.87	2.80	0.88	1.85	35.33	41.40	42.68	39.80	31.80	35.25	38.45	35.17
ICMH IS 16214	1.95	2.84	1.29	2.03	34.30	44.88	49.55	42.91	31.63	41.45	41.10	38.06
ICMX 187001	1.43	1.90	1.09	1.47	49.05	51.50	51.50	50.68	40.10	48.52	44.50	44.38
ICMX 187011	2.52	2.23	1.15	1.96	29.90	41.60	41.40	37.63	25.68	37.07	38.77	33.84
ICMX 187018	2.04	2.91	0.75	1.90	42.85	45.50	53.40	47.25	32.93	41.70	44.47	39.70
ICMX 187020	2.20	3.09	0.93	2.08	39.05	36.75	38.00	37.93	29.50	31.60	33.60	31.57
ICMX 187023	1.18	1.71	2.02	1.64	33.20	41.18	49.08	41.15	32.28	36.05	44.62	37.65
ICMX 187026	0.97	3.19	1.17	1.78	54.55	58.33	61.23	58.03	50.80	48.77	53.32	50.97
ICMX 187031	2.62	1.38	0.72	1.57	35.00	41.08	39.13	38.40	28.93	37.42	33.27	33.21
ICMX 187040	1.50	2.69	0.78	1.66	40.20	37.95	37.45	38.53	33.35	34.87	32.37	33.53

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187041	1.14	2.63	0.93	1.57	43.10	51.18	56.83	50.37	40.78	47.07	52.80	46.88
ICMX 187042	2.09	1.88	1.58	1.85	37.50	38.75	44.25	40.17	27.60	32.50	39.25	33.12
ICMX 187046	0.98	1.87	2.08	1.64	53.45	57.58	60.35	57.12	50.45	50.42	58.90	53.26
ICMX 187048	3.21	2.69	1.31	2.40	33.67	43.43	37.28	38.12	26.83	35.10	35.40	32.44
ICMX 187050	2.24	3.35	1.16	2.25	43.15	41.18	36.43	40.25	36.05	35.87	33.05	34.99
ICMX 187054	2.08	2.30	2.11	2.16	38.68	42.10	46.33	42.37	35.28	35.65	42.87	37.93
ICMX 187068	1.85	3.26	1.45	2.19	38.05	41.33	51.80	43.72	30.70	36.95	47.17	38.28
ICMX 1871038	3.06	4.52	2.06	3.21	27.58	36.98	46.93	37.16	23.33	35.35	39.92	32.87
ICMX 1871039	2.02	3.17	1.99	2.39	33.38	41.00	43.58	39.32	27.25	35.20	41.12	34.53
ICMX 1871040	1.41	2.84	1.66	1.97	27.23	43.68	43.00	37.97	23.50	40.12	38.32	33.98
ICMX 1871041	2.28	2.37	1.39	2.01	35.33	32.85	56.10	41.42	29.68	31.22	49.35	36.75
ICMX 1871042	2.65	3.43	3.12	3.06	34.12	42.33	47.20	41.22	30.58	37.57	37.22	35.13
ICMX 1871043	1.53	3.00	1.59	2.04	31.73	44.63	41.93	39.42	27.40	40.47	35.20	34.36
ICMX 1871044	2.85	2.96	1.67	2.49	35.90	45.70	37.50	39.70	29.18	41.40	35.05	35.21
ICMX 1871045	1.77	1.44	1.23	1.48	46.52	61.98	68.85	59.12	45.38	48.77	58.05	50.73
ICMX 187572	2.05	2.15	0.91	1.70	53.58	42.63	53.55	49.92	30.78	33.62	42.55	35.65

Table 15 cont'd. Mean performance of pearl millet hybrids at Sadore, Gampela, Cinzana and across the three locations.

Genotype	Grain yield (t/ha)				Grain Fe content (mg/kg)				Grain Zn content (mg/kg)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187848	1.95	2.83	1.28	2.02	37.48	42.70	42.98	41.05	27.15	37.42	36.52	33.70
Chakti (C1)	1.40	1.28	1.14	1.27	55.15	60.35	63.03	59.51	52.83	52.85	51.00	52.23
ICMV 167005 (C2)	2.45	2.17	1.75	2.12	36.85	35.50	41.33	37.89	32.28	32.50	36.55	33.78
Fpr	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Vr	**11.99**	**30.3**	**9.45**	**23.28**	**6.78**	**10**	**8.29**	**19.10**	**4.82**	**3.59**	**4.49**	**8.81**
Mean	**1.96**	**2.05**	**1.37**	**1.79**	**40.91**	**47.43**	**48.57**	**45.63**	**34.15**	**40.85**	**41.52**	**38.84**
SE±	**0.163**	**0.168**	**0.156**	**0.09**	**2.821**	**2.719**	**2.58**	**1.56**	**3.02**	**2.89**	**2.854**	**1.69**
LSD	**0.457**	**0.469**	**0.437**	**0.26**	**7.905**	**7.62**	**7.23**	**4.35**	**8.464**	**8.1**	**7.997**	**4.69**
CV (%)	**11.7**	**11.6**	**16.1**	**12.80**	**9.8**	**8.1**	**7.5**	**8.40**	**12.5**	**10**	**9.7**	**10.60**

C1, Check 1; C2, Check 2

3.3.2. Magnitude of heterosis for grain yield, grain Fe and Zn content

The range of standard heterosis over CHAKTI and ICMV 167005 as well as number of hybrids showing significant heterosis in desirable direction was variable according to the traits, the type of hybrids (SCH or TCH) and location (Table 16).

The magnitude of heterosis for grain yield in single cross hybrids at Sadore ranged from -46.81 to 133.48% over CHAKTI and from -69.65 to 33.21% over ICMV 167005 (Table 16). Respectively, 54 (79.41%) and 12 (17.64%) hybrids had positive heterosis, ranged from -66.25 to 228.22% over CHAKTI and from -80.02 to 94.32% over ICMV 167005 at Gampela with 44 (64.70%) and 14 (20.58%) hybrids showed positive heterosis over CHAKTI and ICMV 167005. At Cinzana, 45 (66.17%) and 14 (20.58%) hybrids had positive heterosis respectively over CHAKTI and ICMV 167005, ranged from -46.30 to 146.30% over CHAKTI and fron -61.84 to 69.57% over ICMV 167005. Whereas the grain yield ranged from -27.62 to 114.87% over CHAKTI and from -56.60 to 28.82% over ICMV 167005 across the three locations. Fifty-three represented (77.94%) and 10 (14.70%) of the single cross hybrids had positive heterosis across locations respectively over CHAKTI and ICMV 167005.

Considering per se performance of grain yield of top cross hybrids, 37 (88.09%) from the heterosis rang -30.32 to 129.75% over CHAKTI and 8 (19.04%) from -60.25 to 31.08% over ICMV 167005 showed positive heterosis at Sadore (Table 16). These top cross hybrids heterosis ranged from 7.48 to 251.91% over CHAKTI and from -36.36 to 108.35% over ICMV 167005, whose 42 (100%) and 33 (78.57%) top cross hybrids had positive heterosis over the two checks at Gampela. At Cinzana, 28 (66.66%) ranged from -47.01 to 174.21% and 9 (21.42%) ranged from -65.56 to 78.20% top cross hybrids had positive heterosis respectively over CHAKTI and ICMV 167005. Considering, the mean per se performance of grain yield across the three locations, 42 (100%) from the varied rang of 15.89 to 152.56% and 13 (30.95%) from the varied rang of -30.52 to 51.42% showed heterosis in desirable direction over CHAKTI and ICMV 167005.

Table 16. Yield performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain yield (t/ha)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
Single cross hybrids								
ICMH 1201	49.53	-31.72	-26.50	-0.39	-14.68	-59.58	-52.23	-40.28
ICMH 1301	-19.28	-19.49	4.84	-12.12	-53.95	-52.33	-31.86	-47.31
ICMH 157222	30.97	-6.78	13.47	13.06	-25.28	-44.81	-26.26	-32.22
ICMH 177002	-14.12	-29.70	6.78	-13.14	-51.00	-58.38	-30.61	-47.92
ICMH 177022	63.08	15.67	3.79	29.50	-6.95	-31.52	-32.55	-22.36
ICMH 177111	88.60	12.78	-10.83	33.52	7.61	-33.23	-42.05	-19.95
ICMX 1871003	37.71	21.67	45.95	34.78	-21.43	-27.96	-5.15	-19.20
ICMX 1871018	-6.67	18.86	-30.72	-5.27	-46.75	-29.63	-54.98	-43.21
ICMX 1871023	-8.96	-5.61	48.86	9.44	-48.06	-44.12	-3.26	-34.39
ICMX 1871027	-9.25	-36.48	-1.06	-15.97	-48.22	-62.39	-35.70	-49.62
ICMX 1871032	12.19	-26.73	40.14	7.40	-35.99	-56.62	-8.92	-35.61
ICMX 1871037	54.27	38.04	1.32	33.04	-11.98	-18.27	-34.15	-20.24
ICMX 1871048	-39.57	22.60	9.15	-4.09	-65.52	-27.41	-29.06	-42.50
ICMX 1871049	86.81	-35.93	160.92	67.66	6.58	-62.07	69.57	0.52
ICMX 1871050	59.43	-41.62	146.30	51.38	-9.04	-65.44	60.07	-9.25
ICMX 187760	-19.43	-39.05	3.96	-19.04	-54.03	-63.91	-32.44	-51.46
ICMX 187762	7.81	27.59	57.75	29.35	-38.49	-24.46	2.52	-22.45
ICMX 187763	54.19	-40.37	48.68	20.77	-12.02	-64.70	-3.38	-27.59
ICMX 187765	-46.81	20.19	8.45	-7.79	-69.65	-28.84	-29.52	-44.72
ICMX 187766	57.63	7.64	27.55	31.86	-10.06	-36.27	-17.11	-20.94
ICMX 187769	36.27	33.28	16.81	29.50	-22.25	-21.09	-24.08	-22.36
ICMX 187772	-19.86	-32.19	-17.08	-23.21	-54.27	-59.85	-46.11	-53.96
ICMX 187773	105.38	21.98	19.45	51.77	17.18	-27.78	-22.37	-9.01
ICMX 187775	36.85	26.11	37.59	33.52	-21.92	-25.33	-10.58	-19.95

Table 16. Yield performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain yield (t/ha)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187778	20.93	3.74	74.12	31.00	-31.00	-38.58	13.16	-21.46
ICMX 187781	-16.34	-4.75	13.82	-3.46	-52.27	-43.61	-26.03	-42.12
ICMX 187786	-0.57	10.76	-1.14	3.07	-43.27	-34.43	-35.76	-38.21
ICMX 187788	-24.37	40.92	70.16	25.81	-56.85	-16.57	10.58	-24.58
ICMX 187803	84.44	-16.91	-46.30	11.41	5.24	-50.81	-65.10	-33.21
ICMX 187806	58.85	68.20	71.13	65.70	-9.37	-0.42	11.21	-0.66
ICMX 187807	116.85	8.57	3.17	46.58	23.72	-35.72	-32.95	-12.12
ICMX 187808	7.38	-51.60	-15.05	-19.12	-38.73	-71.34	-44.79	-51.51
ICMX 187826	34.34	-27.67	70.86	24.39	-23.35	-57.18	11.04	-25.42
ICMX 187827	106.95	139.67	54.23	102.28	18.08	41.90	0.23	21.27
ICMX 187829	46.88	171.01	58.27	92.05	-16.20	60.45	2.86	15.14
ICMX 187830	116.85	164.93	55.72	114.87	23.72	56.85	1.20	28.82
ICMX 187832	50.47	99.69	-12.15	48.39	-14.15	18.23	-42.91	-11.04
ICMX 187853	133.48	37.33	29.49	70.26	33.21	-18.69	-15.85	2.08
ICMX 187854	34.70	82.93	11.09	43.90	-23.15	8.31	-27.80	-13.73
ICMX 187856	50.47	200.78	36.71	97.01	-14.15	78.08	-11.16	18.11
ICMX 187857	47.24	-1.64	-19.28	11.01	-15.99	-41.76	-47.54	-33.44
ICMX 187859	9.53	-56.04	-41.29	-27.62	-37.51	-73.97	-61.84	-56.60
ICMX 187860	48.60	12.47	22.62	28.72	-15.21	-33.41	-20.31	-22.83
ICMX 187861	36.63	-10.21	16.55	14.95	-22.04	-46.84	-24.26	-31.08
ICMX 187862	46.02	9.90	17.78	25.49	-16.69	-34.93	-23.46	-24.76
ICMX 187864	48.32	118.78	-19.28	51.93	-15.38	29.53	-47.54	-8.92
ICMX 187865	63.15	0.00	-17.08	18.02	-6.91	-40.79	-46.11	-29.25
ICMX 187867	71.83	-3.27	-27.90	16.92	-1.96	-42.73	-53.15	-29.91
ICMX 187868	11.25	18.00	-5.90	8.42	-36.52	-30.13	-38.84	-35.00
ICMX 187870	32.62	37.41	12.59	28.32	-24.34	-18.64	-26.83	-23.07

Table 16. Yield performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain yield (t/ha)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187872	73.76	164.15	10.21	85.29	-0.86	56.39	-28.38	11.08
ICMX 187875	62.51	2.96	94.10	51.93	-7.28	-39.04	26.14	-8.92
ICMX 187876	43.30	70.77	-28.61	31.16	-18.24	1.11	-53.60	-21.37
ICMX 187877	1.08	105.30	8.10	38.24	-42.33	21.55	-29.75	-17.12
ICMX 187878	19.21	29.93	35.56	27.77	-31.98	-23.07	-11.90	-23.40
ICMX 187880	4.52	-66.25	13.29	-16.60	-40.37	-80.02	-26.37	-50.00
ICMX 187881	50.04	25.80	-1.94	26.44	-14.40	-25.52	-36.27	-24.20
ICMX 187882	-9.25	14.34	12.06	5.04	-48.22	-32.30	-27.17	-37.03
ICMX 187883	104.66	51.91	-35.92	45.08	16.77	-10.06	-58.35	-13.02
ICMX 187885	97.13	134.22	-4.67	79.31	12.47	38.67	-38.04	7.50
ICMX 187889	45.95	228.22	64.00	112.67	-16.73	94.32	6.58	27.50
ICMX 187891	54.98	18.86	97.45	55.55	-11.57	-29.63	28.32	-6.75
ICMX 187892	81.51	124.24	50.18	86.62	3.56	32.76	-2.40	11.89
ICMX 187893	9.68	-25.49	-14.17	-9.21	-37.42	-55.88	-44.22	-45.57
ICMX 187895	117.06	1.79	-19.45	37.69	23.84	-39.73	-47.65	-17.45
ICMX 187897	40.22	70.62	78.17	61.76	-20.00	1.02	15.79	-3.02
ICMX 187989	-9.89	-10.99	-7.22	-9.44	-48.59	-47.30	-39.70	-45.71
ICMX 187995	68.67	12.31	-4.31	28.01	-3.76	-33.50	-37.81	-23.25
Top cross hybrids								
ICMH 177016	33.05	188.62	7.83	77.97	-24.09	70.88	-29.92	6.70
ICMH 177017	45.16	179.35	106.43	108.58	-17.18	65.39	34.15	25.05
ICMH 177018	37.78	134.22	12.85	62.86	-21.39	38.67	-26.66	-2.36
ICMH 177019	-6.02	114.34	60.12	54.21	-46.38	26.90	4.06	-7.55
ICMH 177020	23.66	94.78	38.56	52.08	-29.45	15.32	-9.95	-8.82
ICMH 177023	5.59	170.07	-16.46	54.37	-39.75	59.90	-45.71	-7.45
ICMH IS 16027	8.89	91.74	-12.76	30.37	-37.87	13.52	-43.31	-21.84

Table 16. Yield performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain yield (t/ha)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMH IS 16037	67.96	23.85	-47.01	18.88	-4.17	-26.67	-65.56	-28.73
ICMH IS 16038	46.45	89.87	23.24	54.21	-16.44	12.41	-19.91	-7.55
ICMH IS 16040	96.70	122.06	-39.35	64.75	12.23	31.47	-60.58	-1.23
ICMH IS 16044	25.81	200.16	57.66	94.02	-28.22	77.71	2.46	16.32
ICMH IS 16052	117.56	98.44	26.94	84.19	24.13	17.49	-17.51	10.42
ICMH IS 16075	51.18	113.80	-0.97	56.73	-13.74	26.58	-35.64	-6.04
ICMH IS 16076	46.88	169.68	-3.87	73.09	-16.20	59.67	-37.53	3.77
ICMH IS 16120	51.47	29.46	3.35	29.74	-13.58	-23.35	-32.84	-22.22
ICMH IS 16187	33.98	117.85	-22.54	45.40	-23.56	28.98	-49.66	-12.83
ICMH IS 16214	39.86	121.36	13.47	59.40	-20.20	31.06	-26.26	-4.43
ICMX 187001	2.29	48.09	-3.87	15.89	-41.64	-12.32	-37.53	-30.52
ICMX 187011	80.65	73.66	0.79	54.52	3.07	2.81	-34.50	-7.36
ICMX 187018	46.52	126.42	-33.71	49.57	-16.40	34.06	-56.92	-10.33
ICMX 187020	57.99	141.00	-17.87	63.41	-9.86	42.69	-46.62	-2.03
ICMX 187023	-15.48	32.89	77.90	28.64	-51.78	-21.32	15.62	-22.88
ICMX 187026	-30.32	148.32	3.17	39.81	-60.25	47.02	-32.95	-16.18
ICMX 187031	88.10	7.48	-36.88	23.76	7.32	-36.36	-58.98	-25.80
ICMX 187040	7.46	109.51	-31.51	30.21	-38.69	24.04	-55.49	-21.93
ICMX 187041	-17.99	105.14	-17.87	23.52	-53.21	21.46	-46.62	-25.94
ICMX 187042	49.68	46.38	38.64	45.32	-14.60	-13.34	-9.90	-12.88
ICMX 187046	-29.96	45.60	83.10	29.11	-60.04	-13.80	18.99	-22.59
ICMX 187048	129.75	109.59	15.23	88.91	31.08	24.09	-25.11	13.25
ICMX 187050	60.57	160.87	1.94	76.87	-8.38	54.45	-33.75	6.04
ICMX 187054	48.96	79.35	85.74	70.18	-15.01	6.18	20.71	2.03
ICMX 187068	32.83	154.40	27.82	72.31	-24.21	50.62	-16.93	3.30
ICMX 1871038	119.28	251.91	80.90	152.56	25.11	108.35	17.56	51.42

Table 16. Yield performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain yield (t/ha)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 1871039	44.95	146.92	74.74	88.20	-17.30	46.19	13.56	12.83
ICMX 1871040	1.22	121.43	46.04	55.07	-42.25	31.10	-5.09	-7.03
ICMX 1871041	63.51	84.80	22.18	58.38	-6.71	9.41	-20.59	-5.05
ICMX 1871042	89.61	167.03	174.21	140.91	8.18	58.10	78.20	44.43
ICMX 1871043	9.53	133.90	39.88	60.42	-37.51	38.49	-9.10	-3.82
ICMX 1871044	104.37	130.71	46.92	96.22	16.61	36.59	-4.52	17.64
ICMX 1871045	26.88	12.31	8.54	16.52	-27.61	-33.50	-29.46	-30.14
ICMX 187572	46.95	67.65	-19.72	34.07	-16.16	-0.74	-47.83	-19.62
ICMX 187848	39.86	120.65	12.94	59.09	-20.20	30.64	-26.60	-4.62

The magnitude of heterosis in single cross hybrids for grain Fe ranging from -48.78 to 21.49% over CHAKTI and -23.34 to 81.82% over ICMV 167005 at Sadore; 3 (4.41%) and 51 (75%) single cross hybrids showed heterosis in the desirable sense (Table 17). At Gampela, 9 (13.23%) (ranged from -42.62 to 36.04%) and 61 (89.70%) (ranged from -2.45 to 131.27%) single cross hybrids had positive heterosis respectively over CHAKTI and ICMV 167005. Heterosis ranged from -44.47 to 13.80% (1 in positive sense) over CHAKTI and from -15.32 to 73.55% (60 in positive sense) over ICMV 167005 at Cinzana. While, 3 (ranged from -41.61 to 23.69%) over CHAKTI and 64 (ranged from -8.29 to 94.27%) over ICMV 167005 across the three locations.

Among the top cross hybrids except two (1 at Gampela and 1 at Cinzana) no top cross hybrids showed positive heterosis over CHAKTI for Fe in and across locations (Table 17). Nevertheless 23 (54.76%) (among the range of -26.11 to 48.03%), 41 (97.61%) (among the range of -7.46 to 74.59%), 30 (71.42%) (among the range of -12.90 to 66.59%) and 39 (92.85%) (among the range of -1.93 to 56.03%) had positive heterosis over ICMV 167005 respectively at Sadore, Gampela, Cinzana and across locations.

Table 17. Grain Fe performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Fe content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
Single cross hybrids								
ICMH 1201	13.33	13.75	-1.43	8.25	69.61	93.38	50.33	70.02
ICMH 1301	21.49	36.04	13.80	23.69	81.82	131.27	73.55	94.27
ICMH 157222	-31.01	-25.52	-36.22	-30.99	3.26	26.62	-2.73	8.39
ICMH 177002	-39.71	-40.35	-44.47	-41.61	-9.77	1.41	-15.32	-8.29
ICMH 177022	-25.20	-17.10	-26.70	-23.00	11.94	40.93	11.78	20.93
ICMH 177111	-18.95	-24.61	-25.35	-23.12	21.30	28.17	13.84	20.74
ICMX 1871003	-36.36	-23.56	-19.51	-26.10	-4.75	29.94	22.74	16.07
ICMX 1871018	-48.78	-27.13	-35.22	-36.68	-23.34	23.89	-1.21	-0.55
ICMX 1871023	-34.85	-28.67	-17.61	-26.68	-2.50	21.27	25.65	15.15
ICMX 1871027	-31.37	-18.31	-29.59	-26.33	2.71	38.87	7.38	15.70
ICMX 1871032	-31.70	-15.58	-19.20	-21.83	2.23	43.52	23.23	22.78
ICMX 1871037	-7.47	-10.27	-5.36	-7.68	38.48	52.54	44.33	45.00
ICMX 1871048	-0.76	13.31	-25.67	-4.81	48.52	92.62	13.36	49.51
ICMX 1871049	-26.38	-12.26	-9.44	-15.63	10.18	49.15	38.11	32.52
ICMX 1871050	15.63	10.85	-8.46	5.51	73.05	88.45	39.61	65.72
ICMX 187760	-24.48	-16.74	-28.08	-23.14	13.03	41.55	9.68	20.72
ICMX 187762	-16.50	-25.55	-12.53	-18.17	24.97	26.56	33.39	28.53
ICMX 187763	-22.07	-16.19	-13.96	-17.22	16.64	42.48	31.21	30.01
ICMX 187765	-6.07	-11.76	-6.58	-8.18	40.57	50.00	42.46	44.21
ICMX 187766	-17.53	-21.96	-8.22	-15.75	23.42	32.68	39.97	32.33
ICMX 187769	-24.42	14.13	-1.71	-3.38	13.11	94.03	49.89	51.76
ICMX 187772	-7.02	-8.98	-7.85	-7.98	39.16	54.73	40.53	44.52
ICMX 187773	-32.13	-17.60	-21.10	-23.34	1.57	40.08	20.32	20.40
ICMX 187775	-29.86	-3.23	-31.89	-21.58	4.97	64.51	3.87	23.17

Table 17. Grain Fe performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Fe content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187778	-36.75	-12.34	-29.83	-26.06	-5.35	49.01	7.02	16.13
ICMX 187781	-12.33	8.50	-0.87	-1.24	31.21	84.45	51.17	55.11
ICMX 187786	-24.33	9.61	-15.99	-9.91	13.24	86.34	28.12	41.49
ICMX 187788	-27.38	-14.66	-19.28	-20.23	8.68	45.07	23.11	25.28
ICMX 187803	-26.93	-33.80	-8.85	-22.87	9.36	12.54	39.00	21.14
ICMX 187806	-29.32	-24.69	-24.91	-26.20	5.78	28.03	14.52	15.91
ICMX 187807	-33.09	-27.42	-26.65	-28.90	0.14	23.38	11.86	11.67
ICMX 187808	-37.53	-31.35	-34.63	-34.43	-6.51	16.70	-0.31	2.98
ICMX 187826	-43.61	-29.74	-38.32	-37.05	-15.60	19.44	-5.93	-1.13
ICMX 187827	-27.87	-22.40	-18.80	-22.84	7.95	31.92	23.83	21.19
ICMX 187829	-18.13	-34.80	-26.23	-26.62	22.52	10.85	12.51	15.25
ICMX 187830	-30.28	-15.66	-20.67	-21.95	4.34	43.38	20.98	22.59
ICMX 187832	-36.90	-39.11	-32.37	-36.04	-5.56	3.52	3.15	0.45
ICMX 187853	-30.50	-31.73	-24.35	-28.75	4.02	16.06	15.36	11.90
ICMX 187854	-33.85	-35.05	-25.35	-31.26	-1.00	10.42	13.84	7.97
ICMX 187856	-14.51	-28.50	-15.23	-19.49	27.95	21.55	29.28	26.44
ICMX 187857	-26.84	-26.43	-25.15	-26.11	9.50	25.07	14.15	16.05
ICMX 187859	-34.90	-29.25	-28.76	-30.82	-2.58	20.28	8.64	8.66
ICMX 187860	-25.11	-23.61	-37.20	-28.89	12.08	29.86	-4.23	11.69
ICMX 187861	-16.05	-14.50	-18.69	-16.45	25.64	45.35	24.00	31.22
ICMX 187862	-24.12	-24.06	-17.74	-21.85	13.57	29.10	25.45	22.75
ICMX 187864	-38.66	-27.34	-17.34	-27.31	-8.20	23.52	26.06	14.17
ICMX 187865	-27.96	-20.66	-13.69	-20.47	7.82	34.87	31.62	24.91
ICMX 187867	-34.40	-29.49	-30.35	-31.32	-1.82	19.86	6.22	7.86
ICMX 187868	-9.12	-10.85	-9.84	-9.96	36.01	51.55	37.50	41.41
ICMX 187870	-12.42	-13.04	-11.82	-12.42	31.07	47.83	34.48	37.56

Table 17. Grain Fe performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Fe content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187872	-31.64	-28.42	-27.89	-29.22	2.31	21.69	9.97	11.16
ICMX 187875	-35.54	-29.03	-22.89	-28.89	-3.53	20.65	17.59	11.69
ICMX 187876	-19.49	-27.54	-25.04	-24.18	20.49	23.18	14.32	19.08
ICMX 187877	-25.97	-39.19	-28.64	-31.39	10.80	3.38	8.83	7.76
ICMX 187878	-16.50	-23.40	-23.21	-21.21	24.97	30.23	17.11	23.75
ICMX 187880	-33.49	-29.41	-34.11	-32.33	-0.46	20.00	0.48	6.28
ICMX 187881	-28.23	-33.39	-27.26	-29.64	7.41	13.24	10.94	10.50
ICMX 187882	-22.72	-26.71	-32.49	-27.52	15.66	24.59	2.95	13.83
ICMX 187883	-19.62	-20.75	-25.86	-22.21	20.30	34.73	13.07	22.17
ICMX 187885	-21.99	-12.21	-27.61	-20.67	16.74	49.24	10.40	24.60
ICMX 187889	-34.81	-42.62	-41.41	-39.79	-2.44	-2.45	-10.65	-5.44
ICMX 187891	-9.25	7.29	-13.64	-5.21	35.82	82.39	31.70	48.88
ICMX 187892	-9.19	-14.95	-11.79	-12.07	35.90	44.59	34.53	38.11
ICMX 187893	-9.97	-28.78	-23.48	-21.11	34.74	21.07	16.69	23.91
ICMX 187895	-18.04	-14.70	-17.98	-16.89	22.66	45.01	25.09	30.54
ICMX 187897	-12.46	9.36	-19.64	-7.63	31.02	85.92	22.55	45.08
ICMX 187989	-33.67	-10.52	-9.28	-17.24	-0.73	52.11	38.35	29.98
ICMX 187995	-38.13	-21.13	-34.82	-31.22	-7.41	34.08	-0.60	8.02
Top cross hybrids								
ICMH 177016	-14.69	-20.91	-19.36	-18.45	27.68	34.45	22.99	28.08
ICMH 177017	-19.22	-9.11	-36.73	-22.00	20.90	54.51	-3.51	22.51
ICMH 177018	-42.70	-20.13	-22.97	-28.11	-14.25	35.77	17.47	12.91
ICMH 177019	-16.95	-17.02	-16.42	-16.79	24.29	41.07	27.46	30.69
ICMH 177020	-23.63	-23.28	-15.94	-20.80	14.30	30.42	28.19	24.39
ICMH 177023	-39.38	-25.72	-11.39	-24.89	-9.28	26.28	35.13	17.97
ICMH IS 16027	-31.37	-25.30	-35.03	-30.62	2.71	26.99	-0.92	8.97

Table 17. Grain Fe performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Fe content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMH IS 16037	-32.28	-34.33	-34.87	-33.89	1.36	11.63	-0.68	3.83
ICMH IS 16038	-25.75	-32.23	-42.88	-33.99	11.13	15.21	-12.90	3.67
ICMH IS 16040	-30.64	-45.29	-32.84	-36.38	3.80	-6.99	2.42	-0.08
ICMH IS 16044	-39.56	-21.38	-34.95	-31.79	-9.55	33.66	-0.80	7.13
ICMH IS 16052	-29.56	-27.51	-40.50	-32.73	5.43	23.24	-9.27	5.65
ICMH IS 16075	-35.03	-32.34	-28.53	-31.83	-2.77	15.01	9.00	7.07
ICMH IS 16076	-36.90	-27.51	-30.99	-31.64	-5.56	23.24	5.25	7.36
ICMH IS 16120	-37.62	-21.29	-17.77	-25.11	-6.65	33.80	25.41	17.63
ICMH IS 16187	-35.94	-31.40	-32.29	-33.12	-4.12	16.62	3.27	5.04
ICMH IS 16214	-37.81	-25.63	-21.39	-27.89	-6.92	26.42	19.89	13.25
ICMX 187001	-11.06	-14.66	-18.29	-14.84	33.11	45.07	24.61	33.76
ICMX 187011	-45.78	-31.07	-34.32	-36.77	-18.86	17.18	0.17	-0.69
ICMX 187018	-22.30	-24.61	-15.28	-20.60	16.28	28.17	29.20	24.70
ICMX 187020	-29.19	-39.11	-39.71	-36.26	5.97	3.52	-8.06	0.11
ICMX 187023	-39.80	-31.76	-22.13	-30.85	-9.91	16.00	18.75	8.60
ICMX 187026	-1.09	-3.35	-2.86	-2.49	48.03	64.31	48.15	53.15
ICMX 187031	-36.54	-31.93	-37.92	-35.47	-5.02	15.72	-5.32	1.35
ICMX 187040	-27.11	-37.12	-40.58	-35.25	9.09	6.90	-9.39	1.69
ICMX 187041	-21.85	-15.19	-9.84	-15.36	16.96	44.17	37.50	32.94
ICMX 187042	-32.00	-35.79	-29.80	-32.50	1.76	9.15	7.07	6.02
ICMX 187046	-3.08	-4.59	-4.25	-4.02	45.05	62.20	46.02	50.75
ICMX 187048	-38.95	-28.04	-40.85	-35.94	-8.63	22.34	-9.80	0.61
ICMX 187050	-21.76	-31.76	-42.20	-32.36	17.10	16.00	-11.86	6.23
ICMX 187054	-29.86	-30.24	-26.50	-28.80	4.97	18.59	12.10	11.82
ICMX 187068	-31.01	-31.52	-17.82	-26.53	3.26	16.42	25.33	15.39
ICMX 1871038	-49.99	-38.72	-25.54	-37.56	-25.16	4.17	13.55	-1.93

Table 17. Grain Fe performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Fe content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 1871039	-39.47	-32.06	-30.86	-33.93	-9.42	15.49	5.44	3.77
ICMX 1871040	-50.63	-27.62	-31.78	-36.20	-26.11	23.04	4.04	0.21
ICMX 1871041	-35.94	-45.57	-10.99	-30.40	-4.12	-7.46	35.74	9.32
ICMX 1871042	-38.13	-29.86	-25.12	-30.73	-7.41	19.24	14.20	8.79
ICMX 1871043	-42.47	-26.05	-33.48	-33.76	-13.89	25.72	1.45	4.04
ICMX 1871044	-34.90	-24.28	-40.50	-33.29	-2.58	28.73	-9.27	4.78
ICMX 1871045	-15.65	2.70	9.23	-0.66	26.24	74.59	66.59	56.03
ICMX 187572	-2.85	-29.36	-15.04	-16.11	45.40	20.08	29.57	31.75
ICMX 187848	-32.04	-29.25	-31.81	-31.02	1.71	20.28	3.99	8.34

Regarding grain Zn content, only one (ICMH 1201) single cross hybrid showed positive heterosis over CHAKTI at Sadore and across locations whereas, 5 (7.35%) single cross hybrids had positive heterosis over CHAKTI at Cinzana (Table 18). Over ICMV 167005, heterosis ranged from -26.33 to 76.67% with 48 (70.58%) hybrids in the positive sense, form -8 to 58.62% with 66 (97.05%) hybrids in the positive sense, from -12.53 to 60.25% with 58 (85.29%) hybrids in the positive sense and form -6.54 to 54.91% with 62 (91.17%) hybrids in the positive sense among the single cross respectively at Sadore, Gampela, Cinzana and across locations.

For the top cross hybrids, only 4 (9.50%) at Cinzana and 1 (2.38%) across locations showed positive heterosis over CHAKTI (Table 18). Over ICMV 167005, the heterosis ranged from -27.73 to 57.37% (17 in the positive sense) at Sadore, from -6.15 to 55.14% (37 in the positive sense) at Gampela, from -15.87 to 61.15% (27 in the positive sense) at Cinzana and from -6.54 to 57.67% (32 in the positive sense) across locations. The percentage of the top cross showed positive heterosis was 40.47%, 88.09%, 64.28% and 76.19% respectively at Sadore, Gampela, Cinzana and across locations.

Table 18. Grain Zn performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Zn content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
Single cross hybrids								
ICMH 1201	7.95	-21.72	14.84	0.19	76.67	27.29	60.25	54.91
ICMH 1301	-5.07	-10.18	3.92	-3.87	55.36	46.06	45.01	48.64
ICMH 157222	-33.84	-30.18	-29.41	-31.17	8.27	13.54	-1.50	6.42
ICMH 177002	-40.00	-39.81	-36.57	-38.83	-1.80	-2.12	-11.49	-5.42
ICMH 177022	-33.75	-9.46	-22.94	-22.04	8.43	47.23	7.52	20.54
ICMH 177111	-34.32	-17.79	-26.43	-26.17	7.50	33.69	2.65	14.15
ICMX 1871003	-44.58	-20.15	-19.90	-28.32	-9.29	29.85	11.76	10.83
ICMX 1871018	-54.67	-26.36	-25.69	-35.69	-25.81	19.75	3.69	-0.56
ICMX 1871023	-37.72	-24.47	-8.24	-23.65	1.92	22.83	28.04	18.06
ICMX 1871027	-43.35	-11.35	-23.00	-25.94	-7.28	44.15	7.44	14.51
ICMX 1871032	-39.24	-7.91	-7.31	-18.28	-0.56	49.75	29.33	26.35
ICMX 1871037	-20.16	-8.95	-1.76	-10.40	30.67	48.06	37.07	38.54
ICMX 1871048	-6.81	-15.14	-19.47	-13.75	52.51	38.00	12.37	33.36
ICMX 1871049	-30.10	-17.12	4.06	-14.61	14.41	34.77	45.20	32.03
ICMX 1871050	-6.91	-10.03	-8.20	-8.39	52.35	46.31	28.10	41.65
ICMX 187760	-30.34	-13.91	-17.55	-20.64	14.00	40.00	15.05	22.71
ICMX 187762	-39.52	-20.15	-24.86	-28.22	-1.02	29.85	4.84	10.98
ICMX 187763	-37.19	-7.85	-11.67	-18.99	2.79	49.85	23.26	25.25
ICMX 187765	-17.51	-15.23	3.67	-9.86	35.01	37.85	44.65	39.37
ICMX 187766	-26.31	-12.39	-12.51	-17.14	20.60	42.46	22.08	28.12
ICMX 187769	-32.84	-5.83	-8.43	-15.80	9.91	53.14	27.77	30.20
ICMX 187772	-13.50	-10.31	-2.75	-8.92	41.57	45.85	35.70	40.82
ICMX 187773	-33.60	-43.42	-14.67	-30.75	8.67	-8.00	19.07	7.08
ICMX 187775	-34.54	-19.21	-20.06	-24.66	7.13	31.38	11.55	16.49

Table 18. Grain Zn performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Zn content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187778	-35.49	-23.99	-20.69	-26.80	5.58	23.60	10.67	13.17
ICMX 187781	-18.13	-15.14	-9.12	-14.19	33.98	38.00	26.81	32.68
ICMX 187786	-23.38	-22.89	-9.37	-18.67	25.40	25.38	26.46	25.75
ICMX 187788	-34.54	-21.19	-21.63	-25.85	7.13	28.15	9.36	14.65
ICMX 187803	-37.95	-32.26	-15.45	-28.72	1.55	10.15	17.98	10.21
ICMX 187806	-53.85	-18.41	-30.65	-34.35	-24.47	32.68	-3.23	1.51
ICMX 187807	-40.56	-22.89	-23.43	-29.03	-2.73	25.38	6.84	9.74
ICMX 187808	-52.72	-37.52	-24.41	-38.39	-22.61	1.60	5.47	-4.74
ICMX 187826	-52.34	-27.91	-32.71	-37.72	-22.00	17.23	-6.10	-3.70
ICMX 187827	-40.70	-16.80	-21.67	-26.44	-2.94	35.29	9.30	13.74
ICMX 187829	-37.91	-34.53	-32.25	-34.94	1.61	6.46	-5.47	0.59
ICMX 187830	-36.44	-8.76	-33.39	-26.12	4.03	48.37	-7.06	14.24
ICMX 187832	-43.44	-34.72	-27.25	-35.23	-7.43	6.15	1.50	0.15
ICMX 187853	-35.87	-32.13	-22.41	-30.23	4.96	10.37	8.26	7.87
ICMX 187854	-43.69	-39.32	-15.35	-32.99	-7.84	-1.32	18.11	3.61
ICMX 187856	-28.92	-24.79	-21.18	-25.00	16.33	22.31	9.99	15.96
ICMX 187857	-46.15	-18.26	-16.24	-27.00	-11.86	32.92	16.88	12.88
ICMX 187859	-40.41	-25.45	-17.55	-27.93	-2.48	21.23	15.05	11.43
ICMX 187860	-25.46	-19.58	-25.75	-23.57	22.00	30.77	3.61	18.18
ICMX 187861	-36.40	-17.03	-16.08	-23.26	4.09	34.92	17.10	18.65
ICMX 187862	-21.26	-28.34	-19.51	-23.07	28.87	16.52	12.31	18.95
ICMX 187864	-40.28	-20.96	-18.73	-26.75	-2.26	28.52	13.41	13.26
ICMX 187865	-38.77	-11.79	-17.45	-22.73	0.22	43.45	15.18	19.48
ICMX 187867	-52.11	-27.25	-28.63	-36.09	-21.62	18.31	-0.41	-1.18
ICMX 187868	-16.28	-19.49	-7.84	-14.63	37.02	30.92	28.59	32.00
ICMX 187870	-25.18	-15.89	8.67	-11.03	22.46	36.77	51.63	37.57

Table 18. Grain Zn performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Zn content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 187872	-36.06	-21.67	-18.69	-25.56	4.65	27.38	13.46	15.10
ICMX 187875	-47.13	-34.15	-37.31	-39.56	-13.48	7.08	-12.53	-6.54
ICMX 187876	-37.38	-35.76	-20.94	-31.50	2.48	4.46	10.31	5.92
ICMX 187877	-37.16	-35.00	-20.39	-30.98	2.85	5.69	11.08	6.72
ICMX 187878	-29.91	-29.71	-18.00	-25.96	14.71	14.31	14.42	14.48
ICMX 187880	-34.92	-23.71	-22.45	-27.09	6.51	24.06	8.21	12.73
ICMX 187881	-34.03	-32.26	-12.45	-26.42	7.96	10.15	22.16	13.77
ICMX 187882	-27.35	-24.50	-18.92	-23.65	18.90	22.77	13.13	18.06
ICMX 187883	-36.59	-13.96	-17.90	-22.88	3.78	39.91	14.56	19.24
ICMX 187885	-54.99	-3.69	-22.71	-27.19	-26.33	56.62	7.85	12.58
ICMX 187889	-44.82	-14.19	-33.63	-30.84	-9.70	39.54	-7.39	6.93
ICMX 187891	-35.30	-33.55	-28.78	-32.59	5.89	8.06	-0.63	4.23
ICMX 187892	-38.77	-17.22	-17.94	-24.72	0.22	34.62	14.50	16.40
ICMX 187893	-34.17	-28.72	-24.96	-29.33	7.74	15.91	4.71	9.27
ICMX 187895	-18.64	-14.38	-12.65	-15.26	33.15	39.23	21.89	31.02
ICMX 187897	-38.86	-16.75	-11.47	-22.50	0.06	35.38	23.53	19.83
ICMX 187989	-45.62	-2.46	-10.98	-19.80	-11.00	58.62	24.21	24.01
ICMX 187995	-46.85	-22.42	-27.06	-32.17	-13.01	26.15	1.78	4.88
Top cross hybrids								
ICMH 177016	-27.50	-14.15	-7.84	-16.60	18.65	39.60	28.59	28.95
ICMH 177017	-20.16	-9.33	-30.94	-20.01	30.67	47.45	-3.64	23.68
ICMH 177018	-47.51	-16.75	-14.41	-26.36	-14.10	35.38	19.43	13.85
ICMH 177019	-36.44	-15.57	-11.08	-21.16	4.03	37.29	24.08	21.91
ICMH 177020	-34.98	-8.04	-14.57	-19.24	6.41	49.54	19.21	24.87
ICMH 177023	-45.86	-16.93	-9.08	-24.12	-11.40	35.08	26.87	17.32
ICMH IS 16027	-37.67	-29.90	-32.75	-33.45	2.01	14.00	-6.16	2.90

Table 18. Grain Zn performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Zn content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMH IS 16037	-44.67	-32.64	-34.31	-37.24	-9.45	9.54	-8.34	-2.96
ICMH IS 16038	-35.87	-41.82	-39.71	-39.13	4.96	-5.38	-15.87	-5.89
ICMH IS 16040	-34.73	-42.29	-29.22	-35.50	6.82	-6.15	-1.23	-0.27
ICMH IS 16044	-42.74	-23.08	-26.18	-30.73	-6.29	25.08	3.01	7.10
ICMH IS 16052	-32.37	-20.78	-36.27	-29.73	10.69	28.83	-11.08	8.64
ICMH IS 16075	-40.37	-27.06	-19.86	-29.20	-2.42	18.62	11.82	9.47
ICMH IS 16076	-39.43	-30.94	-33.33	-34.58	-0.87	12.31	-6.98	1.15
ICMH IS 16120	-39.43	-17.09	-13.14	-23.34	-0.87	34.83	21.20	18.53
ICMH IS 16187	-39.81	-33.30	-24.61	-32.66	-1.49	8.46	5.20	4.11
ICMH IS 16214	-40.13	-21.57	-19.41	-27.13	-2.01	27.54	12.45	12.67
ICMX 187001	-24.10	-8.19	-12.75	-15.03	24.23	49.29	21.75	31.38
ICMX 187011	-51.39	-29.86	-23.98	-35.21	-20.45	14.06	6.07	0.18
ICMX 187018	-37.67	-21.10	-12.80	-23.99	2.01	28.31	21.67	17.53
ICMX 187020	-44.16	-40.21	-34.12	-39.56	-8.61	-2.77	-8.07	-6.54
ICMX 187023	-38.90	-31.79	-12.51	-27.91	0.00	10.92	22.08	11.46
ICMX 187026	-3.84	-7.72	4.55	-2.41	57.37	50.06	45.88	50.89
ICMX 187031	-45.24	-29.20	-34.76	-36.42	-10.38	15.14	-8.97	-1.69
ICMX 187040	-36.87	-34.02	-36.53	-35.80	3.31	7.29	-11.44	-0.74
ICMX 187041	-22.81	-10.94	3.53	-10.24	26.33	44.83	44.46	38.78
ICMX 187042	-47.76	-38.51	-23.04	-36.59	-14.50	0.00	7.39	-1.95
ICMX 187046	-4.51	-4.60	15.49	1.97	56.29	55.14	61.15	57.67
ICMX 187048	-49.21	-33.59	-30.59	-37.89	-16.88	8.00	-3.15	-3.97
ICMX 187050	-31.76	-32.13	-35.20	-33.01	11.68	10.37	-9.58	3.58
ICMX 187054	-33.22	-32.54	-15.94	-27.38	9.29	9.69	17.29	12.29
ICMX 187068	-41.89	-30.09	-7.51	-26.71	-4.89	13.69	29.06	13.32
ICMX 1871038	-55.84	-33.11	-21.73	-37.07	-27.73	8.77	9.22	-2.69

Table 18. Grain Zn performance of pearl millet hybrids over CHAKTI and ICMV 167005 at Sadore, Gampela, Cinzana and across the three locations.

Hybrids	Grain Zn content (mg/kg)							
	Heterosis over CHAKTI (%)				Heterosis over ICMV 167005 (%)			
	Sadore	Gampela	Cinzana	Across location	Sadore	Gampela	Cinzana	Across location
ICMX 1871039	-48.42	-33.40	-19.37	-33.89	-15.58	8.31	12.50	2.22
ICMX 1871040	-55.52	-24.09	-24.86	-34.94	-27.20	23.45	4.84	0.59
ICMX 1871041	-43.82	-40.93	-3.24	-29.64	-8.05	-3.94	35.02	8.79
ICMX 1871042	-42.12	-28.91	-27.02	-32.74	-5.27	15.60	1.83	4.00
ICMX 1871043	-48.14	-23.42	-30.98	-34.21	-15.12	24.52	-3.69	1.72
ICMX 1871044	-44.77	-21.67	-31.27	-32.59	-9.60	27.38	-4.10	4.23
ICMX 1871045	-14.10	-7.72	13.82	-2.87	40.58	50.06	58.82	50.18
ICMX 187572	-41.74	-36.39	-16.57	-31.74	-4.65	3.45	16.42	5.54
ICMX 187848	-48.61	-29.20	-28.39	-35.48	-15.89	15.14	-0.08	-0.24

3.4. Assessment of Adaptability and Stability of Hybrids of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) in Sadore, Gampela and Cinzana.

3.4.1. Means and genetic variability

Wide ranges were observed for all traits, based on the means for each genotype across three environments (Table 19). Days to 50% flowering was ranging from 49 days to 65 days; plant height varied from 122.20 cm to 220.50 cm, panicle length from 22.67 cm to 53.50 cm, panicle circumference from 7.17 cm to 10.83 cm, grain yield from 0.92 t/ha to 3.21 t/ha, from 37.16 mg/kg to 73.61 mg/kg and from 31.57 mg/kg to 53.26 mg/kg for grain Fe and Zn content respectively. The overall means were 57 days for days to 50% flowering, 185.23 cm for plant height, 35.49 cm for panicle length, 8.73 cm for panicle circumference, 1.79 t/ha for grain yield, 45.63 mg/kg and 38.84 mg/kg respectively for grain Fe and Zn content.

Table 19. Mean performance of peal millet hybrids across Sadore, Gampela and Cinzana.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
Single cross hybrid							
ICMH 1201	48.50	157.50	25.00	10.33	1.27	64.42	52.33
ICMH 1301	49.67	159.50	22.67	10.67	1.12	73.61	50.21
ICMH 157222	57.00	143.50	47.83	8.17	1.44	41.07	35.95
ICMH 177002	54.33	138.50	40.17	7.83	1.10	34.75	31.95
ICMH 177022	60.50	204.80	38.00	8.33	1.65	45.82	40.72
ICMH 177111	59.33	208.20	38.50	8.33	1.70	45.75	38.56
ICMX 1871003	55.67	133.30	34.00	8.00	1.71	43.98	37.44
ICMX 1871018	62.67	127.20	34.83	7.33	1.20	37.68	33.59
ICMX 1871023	58.17	163.70	37.33	7.33	1.39	43.63	39.88
ICMX 1871027	52.00	177.70	38.50	7.83	1.07	43.84	38.68
ICMX 1871032	54.33	133.30	33.83	8.00	1.37	46.52	42.68
ICMX 1871037	50.17	210.80	38.33	9.50	1.69	54.94	46.80
ICMX 1871048	52.67	179.00	33.33	9.33	1.22	56.65	45.05
ICMX 1871049	55.67	186.50	34.00	9.00	2.13	50.21	44.60
ICMX 1871050	53.83	158.30	32.67	10.00	1.92	62.79	47.85
ICMX 187760	53.50	162.00	30.50	8.83	1.03	45.74	41.45
ICMX 187762	53.00	177.30	29.17	10.33	1.64	48.70	37.49
ICMX 187763	54.17	165.20	30.67	9.00	1.54	49.26	42.31
ICMX 187765	54.00	154.00	26.00	9.17	1.17	54.64	47.08
ICMX 187766	52.00	196.80	32.83	9.00	1.68	50.14	43.28
ICMX 187769	59.83	183.20	29.33	8.67	1.65	57.50	43.98
ICMX 187772	55.83	164.30	23.17	10.33	0.98	54.76	47.57
ICMX 187773	53.83	182.00	28.83	9.67	1.93	45.62	36.17
ICMX 187775	52.50	186.50	28.67	9.33	1.70	46.67	39.35
ICMX 187778	52.83	197.70	30.00	8.50	1.67	44.00	38.23

Table 19. Mean performance of peal millet hybrids across Sadore, Gampela and Cinzana.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
ICMX 187781	52.17	169.80	31.83	8.83	1.23	58.77	44.82
ICMX 187786	51.83	191.80	33.00	8.33	1.31	53.61	42.48
ICMX 187788	50.17	196.00	25.33	10.83	1.60	47.47	38.73
ICMX 187803	57.17	187.80	37.17	8.67	1.42	45.90	37.23
ICMX 187806	60.00	192.00	36.33	9.50	2.11	43.92	34.29
ICMX 187807	52.17	196.20	40.00	7.83	1.86	42.31	37.07
ICMX 187808	58.17	176.20	36.00	8.17	1.03	39.02	32.18
ICMX 187826	53.50	152.80	38.67	8.33	1.58	37.46	32.53
ICMX 187827	55.67	198.80	27.83	10.50	2.57	45.92	38.42
ICMX 187829	58.33	190.00	26.17	10.83	2.44	43.67	33.98
ICMX 187830	54.83	214.00	33.33	9.33	2.73	46.45	38.59
ICMX 187832	55.83	212.20	32.33	9.83	1.89	38.06	33.83
ICMX 187853	56.17	200.00	31.83	8.50	2.16	42.40	36.44
ICMX 187854	56.17	184.30	30.83	9.33	1.83	40.91	35.00
ICMX 187856	58.33	179.50	29.17	10.33	2.50	47.91	39.17
ICMX 187857	53.67	163.00	33.50	8.00	1.41	43.97	38.13
ICMX 187859	54.83	178.50	33.17	8.83	0.92	41.17	37.64
ICMX 187860	54.83	183.70	36.00	8.33	1.64	42.32	39.92
ICMX 187861	53.17	170.20	27.67	9.83	1.46	49.72	40.08
ICMX 187862	58.17	188.00	33.33	8.83	1.60	46.51	40.18
ICMX 187864	60.33	199.50	32.17	9.00	1.93	43.26	38.26
ICMX 187865	54.83	191.00	36.50	7.17	1.50	47.33	40.36
ICMX 187867	56.67	197.30	34.17	8.17	1.49	40.87	33.38
ICMX 187868	54.00	179.00	30.00	9.17	1.38	53.58	44.59
ICMX 187870	57.50	201.00	33.50	9.83	1.63	52.12	46.47
ICMX 187872	61.17	191.20	34.83	9.50	2.36	42.12	38.88
ICMX 187875	57.50	185.30	39.67	7.83	1.93	42.32	31.57

Table 19. Mean performance of peal millet hybrids across Sadore, Gampela and Cinzana.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
ICMX 187876	55.67	211.20	33.33	9.00	1.67	45.12	35.78
ICMX 187877	60.00	202.50	31.33	9.33	1.76	40.83	36.05
ICMX 187878	53.33	190.00	34.00	7.33	1.62	46.89	38.67
ICMX 187880	54.00	194.70	37.50	8.17	1.06	40.27	38.08
ICMX 187881	55.33	193.00	42.33	8.00	1.61	41.87	38.43
ICMX 187882	50.83	183.20	31.17	8.83	1.34	43.13	39.88
ICMX 187883	59.83	198.50	34.50	9.50	1.84	46.29	40.28
ICMX 187885	61.50	207.70	31.50	8.83	2.28	47.21	38.03
ICMX 187889	60.17	198.30	38.00	8.83	2.70	35.83	36.12
ICMX 187891	58.00	198.00	31.83	9.17	1.98	56.41	35.21
ICMX 187892	61.33	179.80	30.00	9.00	2.37	52.33	39.32
ICMX 187893	55.33	185.20	35.00	9.00	1.15	46.95	36.91
ICMX 187895	55.50	193.80	37.33	9.33	1.75	49.46	44.26
ICMX 187897	53.00	186.80	30.50	9.17	2.06	54.97	40.48
ICMX 187989	54.50	148.80	37.17	7.67	1.15	49.25	41.89
ICMX 187995	60.67	152.80	39.83	7.50	1.63	40.93	35.43
Top cross hybrid							
ICMH 177016	59.50	207.70	43.00	8.83	2.26	48.53	43.56
ICMH 177017	59.17	213.50	42.17	9.00	2.65	46.42	41.78
ICMH 177018	60.17	204.20	36.17	8.83	2.07	42.78	38.46
ICMH 177019	55.33	188.20	34.17	9.67	1.96	49.52	41.18
ICMH 177020	60.83	191.30	39.83	8.67	1.93	47.13	42.18
ICMH 177023	59.83	179.70	33.50	9.50	1.96	44.70	39.63
ICMH IS 16027	58.83	207.00	44.67	7.67	1.66	41.29	34.76
ICMH IS 16037	62.17	187.80	47.83	7.67	1.51	39.34	32.78
ICMH IS 16038	57.67	204.70	47.50	7.33	1.96	39.28	31.79
ICMH IS 16040	61.67	205.20	36.67	8.67	2.09	37.86	33.69

Table 19. Mean performance of peal millet hybrids across Sadore, Gampela and Cinzana.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
ICMH IS 16044	55.67	197.30	40.50	7.67	2.47	40.59	36.18
ICMH IS 16052	57.67	174.20	44.83	7.67	2.34	40.03	36.70
ICMH IS 16075	61.67	198.70	35.17	8.67	1.99	40.57	36.98
ICMH IS 16076	61.33	205.80	46.17	8.00	2.20	40.68	34.17
ICMH IS 16120	60.83	201.00	40.50	7.83	1.65	44.57	40.04
ICMH IS 16187	63.17	192.00	43.50	8.00	1.85	39.80	35.17
ICMH IS 16214	61.17	196.70	43.33	8.50	2.03	42.91	38.06
ICMX 187001	54.33	184.50	35.83	8.83	1.47	50.68	44.38
ICMX 187011	61.00	189.20	38.17	9.67	1.96	37.63	33.84
ICMX 187018	62.33	185.90	31.17	8.17	1.90	47.25	39.70
ICMX 187020	64.83	194.30	46.83	7.50	2.08	37.93	31.57
ICMX 187023	57.67	191.80	38.67	7.83	1.64	41.15	37.65
ICMX 187026	51.17	168.20	29.17	8.67	1.78	58.03	50.97
ICMX 187031	57.67	188.70	29.83	9.50	1.57	38.40	33.21
ICMX 187040	57.67	195.50	39.17	7.33	1.66	38.53	33.53
ICMX 187041	53.83	160.80	29.33	10.00	1.57	50.37	46.88
ICMX 187042	57.50	179.80	40.50	7.83	1.85	40.17	33.12
ICMX 187046	53.83	163.50	28.33	9.00	1.64	57.12	53.26
ICMX 187048	56.33	195.50	43.83	8.33	2.40	38.12	32.44
ICMX 187050	62.33	178.30	39.00	8.33	2.25	40.25	34.99
ICMX 187054	58.00	184.30	45.50	8.33	2.16	42.37	37.93
ICMX 187068	53.67	188.80	33.83	8.33	2.19	43.72	38.28
ICMX 1871038	57.83	186.30	35.83	8.50	3.21	37.16	32.87
ICMX 1871039	58.33	201.30	45.67	7.67	2.39	39.32	34.53
ICMX 1871040	60.00	192.80	46.00	7.67	1.97	37.97	33.98
ICMX 1871041	60.67	202.80	49.33	7.17	2.01	41.42	36.75
ICMX 1871042	58.00	204.20	39.50	9.50	3.06	41.22	35.13

Table 19. Mean performance of peal millet hybrids across Sadore, Gampela and Cinzana.

Genotype	Days to 50% flowering	Plant height (cm)	Panicle length (cm)	Panicle circumference (cm)	Grain yield (t/ha)	Grain Fe content (mg/kg)	Grain Zn content (mg/kg)
ICMX 1871043	58.33	197.70	38.00	8.33	2.04	39.42	34.36
ICMX 1871044	60.17	195.70	32.83	8.50	2.49	39.70	35.21
ICMX 1871045	54.67	127.50	26.67	9.17	1.48	59.12	50.73
ICMX 187572	55.50	220.50	53.50	7.67	1.70	49.92	35.65
ICMX 187848	57.83	185.70	28.17	10.50	2.02	41.05	33.70
CHAKTI (C1)	48.00	153.70	22.00	9.17	1.27	59.51	52.23
ICMV 167005 (C2)	62.50	229.70	40.33	9.00	2.12	37.89	33.78
Fpr	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Vr	**8.01**	**9.21**	**14.53**	**6.52**	**23.28**	**19.10**	**8.81**
Mean	**56.72**	**185.23**	**35.49**	**8.73**	**1.79**	**45.63**	**38.84**
SE±	**1.26**	**6.59**	**1.63**	**0.35**	**0.09**	**1.56**	**1.69**
LSD	**3.49**	**18.35**	**4.53**	**0.96**	**0.26**	**4.35**	**4.69**
CV (%)	**5.40**	**8.70**	**11.20**	**9.70**	**12.80**	**8.40**	**10.60**

C1, check 1; C2, Check 2

Analysis of variance partitioned the total variances into its components following AMMI model revealed highly significant ($p<0.01$) genotypic differences among the traits (Table 20). AMMI analysis of variance for stability showed that genotypes ($p<0.01$), environments ($p<0.01$) and G×E ($p<0.01$) pattern were highly significant, showing the wider range of diversity among the genotypes (Table 20). Total genotypic variation indicated that main effects of genotype, environment and G × E interaction accounted for 37.54%, 45.68% and 16.78% variation for days to 50% flowering, for 53.30%, 24.36% and 22.35% for plant height, for 73.09%, 9.13% and 17.78% for panicle length, for 63.61%, 9.83% and 26.53% for panicle circumference, for 36.61%, 16.42% and 46.98% for grain yield, for 64.39%, 15.82% and 19.79% for grain Fe and for 52.25%, 23.27% and 24.48% for grain Zn content. Genotypic factors accounted for larger proportion of the treatment sum of squares over environments for all the traits except for days to 50% flowering whereas, the contribution of G×E interaction contributed a greater proportion for grain yield. The G×E interaction was significant ($p<0.05$) for almost all the traits and it was further partitioned into two interaction principal component axes (IPCA) with the contribution of 66.64% and 33.36% for days to 50% flowering, of 65.17%

Table 20. Analysis of variance of pearl millet hybrids using AMMI model across Sadore, Gampela and Cinzana.

Source	df	Days to 50% flowering	Plant height	Panicle length	Panicle circumference	Grain yield	Grain Fe content	Grain Zn content
Total	671	38.6	899	60.3	1.574	0.58	79.40	56.10
Treatments	335	66.80**	1493.00**	104.80**	2.42**	1.11**	144.20**	95.40**
Genotypes (G)	111	75.70**	2402.00**	231.10**	4.65**	1.23**	280.20**	150.50**
Environments (E)	2	5112.10**	60915.00**	1603.00**	39.94**	30.43**	3820.40**	3719.30**
Block	3	126.10**	5308.00**	30.00^{NS}	2.70**	0.93**	38.40*	2.10^{NS}
G X E	222	16.90**	503.00**	28.10**	0.97**	0.79**	43.10**	35.30**
IPCA 1	112	22.30**	650.00**	32.10**	1.01**	1.06**	46.40**	42.10**
IPCA 2	110	11.40^{NS}	354.00*	24.10**	0.93*	0.51**	39.70**	28.30**
Error	333	9.4	261	15.9	0.713	0.05	14.70	17.10
% treatment SS due to G	111	37.54	53.30	73.09	63.61	36.61	64.39	52.25
% treatment SS due to E	2	45.68	24.36	9.13	9.86	16.41	15.82	23.27
% treatment SS due to $G * E$	222	16.78	22.35	17.78	26.53	46.98	19.79	24.48
% $G * E$ SS due to IPCA1	112	66.64	65.17	57.55	52.63	68.00	54.34	60.19
% $G * E$ SS due to IPCA2	110	33.36	34.83	42.45	47.42	32.00	45.66	39.81

*,** F probability significant at P 0.05 and 0.01, respectively; NS, non-significant F probability

and 34.83% for plant height, of 57.55% and 42.45% for panicle length, of 52.63% and 42.42% for panicle circumference, of 68% and 32% for grain yield, of 54.34% and 45.66% for Fe and of 60.19% and 39.81% for Zn respectively for IPCA1 and IPCA2 (Table 20). The interaction of principal component in axis-2 (IPCA2) mean sum of squares were non-significant for days to 50% flowering which had much reduced magnitude compared to IPCA1.

3.4.2. AMMI adaptability, stability value (ASV) and stability index (SI)

Based on the means and on the IPCA scores, 51 hybrids (46.36%) (20 SCH and 31 TCH) (Table 21) had grain yield greater than the overall mean and among them, 9 (17.64%) (3 SCH and 5 TCH) (ICMH IS 16052, ICMX 187806, ICMX 187883, ICMX 187897, ICMX 187011, ICMX 187048, ICMX 187054, ICMX 1871041 and ICMX 1871042) had IPCA scores close to zero whereas. For grain Fe (Table 22) content 49 hybrids (44.54%) (38 SCH and 11TCH) showed mean value greater than the grand mean with 3 (6.12%) hybrids (2 SCH and 1 TCH) (ICMX 187895, ICMX 187989, ICMX 187001) having IPCA scores close to zero. Seven hybrids

(15.90%) (5 SCH and 2 TCH) (ICMX 1871023, ICMX 1871037, ICMX 1871049, ICMX 187766, ICMX 187872, ICMH 177013 and ICMH 177017) from 44 (40%) (32 SCH and 12 TCH) (Table 23) showed mean value for grain Zn content greater than the grand mean had IPCA scores close to zero.

According to the AMMI stability value (ASV) many hybrids depending on the traits (grain yield, grain Fe and Zn content) showed least scores. Among them, the hybrids ICMX 1871018 showed the least score for grain yield (Table 21), ICMH IS 16187 for grain Fe content (Table 22) and ICMX 187778 for grain Zn (Table 23).

The sum of the yield, grain Fe and Zn content and their stability rankings (YSI, FeSI and ZnSI) ranked ICMX 187827 (Table 21), ICMX 187026 (Table 22) and ICMX 1871037 (Table 23) as the hybrids that combined high yield, high grain Fe and Zn content with stability respectively among the hybrids showed high mean values and more stability.

Among the checks, ICMV showed high grain yield adaptability and stability while CHAKTI had high mean performance and stability for Fe.

Table 21. Ranking of genotypes based on grain yield, AMMI stability value (ASV) and grain yield stability index (YSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	YSI (A+B)	YSI rank
ICMH 1201	1.27	98	0.28	-0.21	0.42	56	154	95
ICMH 1301	1.12	105	0.15	0.20	0.23	23	128	70
ICMH 157222	1.44	89	0.22	0.01	5.78	104	193	108
ICMH 177002	1.10	106	0.21	0.18	0.30	34	140	87
ICMH 177022	1.65	68	0.18	-0.16	0.26	28	96	36
ICMH 177111	1.70	59	0.21	-0.32	0.35	44	103	45
ICMX 1871003	1.71	56	0.18	0.09	0.36	47	103	46
ICMX 1871018	1.20	101	-0.03	0.02	0.04	1	102	44
ICMX 1871023	1.39	92	0.20	0.30	0.33	40	132	76
ICMX 1871027	1.07	107	0.23	0.13	0.42	54	161	99
ICMX 1871032	1.37	94	0.30	0.18	0.55	70	164	102
ICMX 1871037	1.69	60	0.07	-0.13	0.14	7	67	18
ICMX 1871048	1.22	100	-0.04	0.31	0.31	35	135	79
ICMX 1871049	2.13	23	0.70	0.27	1.84	94	117	62

Table 21. Ranking of genotypes based on grain yield, AMMI stability value (ASV) and grain yield stability index (YSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	YSI (A+B)	YSI rank
ICMX 1871050	1.92	45	0.64	0.34	1.26	90	135	80
ICMX 187760	1.03	109	0.23	0.19	0.33	39	148	91
ICMX 187762	1.64	69	0.12	0.27	0.27	30	99	40
ICMX 187763	1.54	82	0.45	0.02	8.87	107	189	106
ICMX 187765	1.17	102	-0.04	0.33	0.33	41	143	88
ICMX 187766	1.68	61	0.24	-0.06	1.01	86	147	90
ICMX 187769	1.65	67	0.08	0.00	3.77	100	167	103
ICMX 187772	0.98	111	0.16	0.12	0.25	27	138	84
ICMX 187773	1.93	44	0.27	-0.29	0.38	51	95	33
ICMX 187775	1.70	58	0.15	0.07	0.33	37	95	34
ICMX 187778	1.67	63	0.27	0.26	0.38	49	112	54
ICMX 187781	1.23	99	0.12	0.22	0.23	22	121	66
ICMX 187786	1.31	96	0.07	0.10	0.11	5	101	42
ICMX 187788	1.60	77	0.03	0.45	0.45	60	137	83
ICMX 187803	1.42	90	0.26	-0.43	0.46	61	151	93
ICMX 187806	2.11	25	0.09	0.09	0.13	6	31	3
ICMX 187807	1.86	48	0.31	-0.40	0.47	63	111	53
ICMX 187808	1.03	110	0.29	0.01	12.22	110	220	112
ICMX 187826	1.58	79	0.41	0.19	0.90	80	159	96
ICMX 187827	2.57	6	-0.11	-0.16	0.18	14	20	1
ICMX 187829	2.44	10	-0.34	0.12	1.01	84	94	32
ICMX 187830	2.73	3	-0.19	-0.20	0.27	29	32	4
ICMX 187832	1.89	47	-0.19	-0.15	0.28	32	79	22
ICMX 187853	2.16	21	0.28	-0.38	0.43	57	78	21
ICMX 187854	1.83	52	-0.12	0.00	3.51	99	151	94
ICMX 187856	2.50	7	-0.49	0.03	7.50	106	113	55
ICMX 187857	1.41	91	0.17	-0.17	0.25	26	117	63
ICMX 187859	0.92	112	0.27	-0.09	0.77	78	190	107

Table 21. Ranking of genotypes based on grain yield, AMMI stability value (ASV) and grain yield stability index (YSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	YSI (A+B)	YSI rank
ICMX 187860	1.64	71	0.20	-0.03	1.12	88	159	97
ICMX 187861	1.46	88	0.25	-0.01	9.48	108	196	109
ICMX 187862	1.60	78	0.19	-0.04	0.93	81	159	98
ICMX 187864	1.93	43	-0.28	-0.16	0.50	67	110	51
ICMX 187865	1.50	84	0.20	-0.24	0.29	33	117	64
ICMX 187867	1.49	85	0.21	-0.31	0.34	43	128	71
ICMX 187868	1.38	93	0.05	0.03	0.10	3	96	37
ICMX 187870	1.63	73	0.05	0.00	0.69	75	148	92
ICMX 187872	2.36	14	-0.35	-0.17	0.75	76	90	28
ICMX 187875	1.93	42	0.39	0.15	1.01	85	127	69
ICMX 187876	1.67	62	-0.12	-0.18	0.20	20	82	23
ICMX 187877	1.76	54	-0.27	0.14	0.56	72	126	68
ICMX 187878	1.62	75	0.10	0.14	0.16	10	85	25
ICMX 187880	1.06	108	0.39	0.12	1.34	91	199	110
ICMX 187881	1.61	76	0.11	-0.12	0.15	9	85	26
ICMX 187882	1.34	95	0.06	0.18	0.18	15	110	52
ICMX 187883	1.84	51	0.05	-0.47	0.48	64	115	57
ICMX 187885	2.28	16	-0.22	-0.32	0.35	45	61	15
ICMX 187889	2.70	4	-0.55	0.15	2.04	96	100	41
ICMX 187891	1.98	35	0.32	0.20	0.55	71	106	49
ICMX 187892	2.37	13	-0.11	-0.07	0.20	19	32	5
ICMX 187893	1.15	103	0.20	0.00	10.42	109	212	111
ICMX 187895	1.75	55	0.30	-0.48	0.51	68	123	67
ICMX 187897	2.06	29	0.06	0.20	0.20	21	50	10
ICMX 187989	1.15	104	0.12	0.12	0.17	12	116	58
ICMX 187995	1.63	74	0.19	-0.21	0.27	31	105	47
ICMH 177016	2.26	17	-0.52	0.01	43.64	112	129	73
ICMH 177017	2.65	5	-0.29	0.29	0.41	53	58	13

Table 21. Ranking of genotypes based on grain yield, AMMI stability value (ASV) and grain yield stability index (YSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	YSI (A+B)	YSI rank
ICMH 177018	2.07	28	-0.30	0.00	20.52	111	139	85
ICMH 177019	1.96	40	-0.23	0.35	0.38	50	90	29
ICMH 177020	1.93	41	-0.13	0.14	0.19	17	58	14
ICMH 177023	1.96	38	-0.55	0.04	7.48	105	143	89
ICMH IS 16027	1.66	64	-0.24	0.03	2.08	98	162	100
ICMH IS 16037	1.51	83	0.07	-0.36	0.36	46	129	74
ICMH IS 16038	1.96	39	-0.10	-0.01	0.76	77	116	59
ICMH IS 16040	2.09	26	-0.23	-0.44	0.46	62	88	27
ICMH IS 16044	2.47	9	-0.49	0.21	1.18	89	98	39
ICMH IS 16052	2.34	15	0.01	-0.31	0.31	36	51	11
ICMH IS 16075	1.99	34	-0.22	-0.11	0.45	59	93	31
ICMH IS 16076	2.20	19	-0.45	-0.10	2.06	97	116	60
ICMH IS 16120	1.65	66	0.10	-0.11	0.15	8	74	20
ICMH IS 16187	1.85	49	-0.31	-0.11	0.86	79	128	72
ICMH IS 16214	2.03	31	-0.25	-0.01	4.63	103	134	78
ICMX 187001	1.47	87	-0.07	0.08	0.11	4	91	30
ICMX 187011	1.96	37	-0.01	-0.24	0.24	25	62	16
ICMX 187018	1.90	46	-0.34	-0.20	0.59	73	119	65
ICMX 187020	2.08	27	-0.34	-0.20	0.62	74	101	43
ICMX 187023	1.64	72	0.09	0.44	0.44	58	130	75
ICMX 187026	1.78	53	-0.50	0.26	1.00	83	136	82
ICMX 187031	1.57	80	0.19	-0.41	0.42	55	135	81
ICMX 187040	1.66	65	-0.34	-0.03	4.24	102	167	104
ICMX 187041	1.57	81	-0.35	0.13	0.97	82	163	101
ICMX 187042	1.85	50	0.10	0.02	0.49	66	116	61
ICMX 187046	1.64	70	0.03	0.52	0.52	69	139	86
ICMX 187048	2.40	11	-0.02	-0.40	0.40	52	63	17
ICMX 187050	2.25	18	-0.38	-0.14	1.04	87	105	48

Table 21. Ranking of genotypes based on grain yield, AMMI stability value (ASV) and grain yield stability index (YSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	YSI (A+B)	YSI rank
ICMX 187054	2.16	22	0.06	0.19	0.19	18	40	7
ICMX 187068	2.19	20	-0.36	0.07	1.81	93	113	56
ICMX 1871038	3.21	1	-0.47	-0.11	1.98	95	96	38
ICMX 1871039	2.39	12	-0.23	0.18	0.34	42	54	12
ICMX 1871040	1.97	36	-0.27	0.27	0.38	48	84	24
ICMX 1871041	2.01	33	-0.05	-0.09	0.09	2	35	6
ICMX 1871042	3.06	2	-0.04	0.33	0.33	38	40	8
ICMX 1871043	2.04	30	-0.31	0.21	0.49	65	95	35
ICMX 1871044	2.49	8	-0.10	-0.18	0.19	16	24	2
ICMX 1871045	1.48	86	0.13	0.01	1.45	92	178	105
ICMX 187572	1.70	57	-0.09	-0.17	0.17	13	70	19
ICMX 187848	2.02	32	-0.25	-0.02	3.99	101	133	77
CHAKTI (C1)	1.27	97	0.11	0.10	0.16	11	108	50
ICMV 167005 (C2)	2.12	24	0.09	-0.04	0.23	24	48	9

C1: check 1 and C2: check 2

Table 22. Ranking of genotypes based on grain Fe content, AMMI stability value (ASV) and Fe stability index (FeSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA 1	IPCA 2	ASV	AVS rank (B)	FeSI (A+B)	FeSI rank
ICMH 1201	64.42	2	-0.67	0.62	0.96	60	62	17
ICMH 1301	73.61	1	-1.18	-0.14	9.76	109	110	50
ICMH 157222	41.07	79	-0.53	0.40	0.81	49	128	69
ICMH 177002	34.75	112	-0.12	0.61	0.61	35	147	86
ICMH 177022	45.82	48	-0.48	0.11	2.13	90	138	80
ICMH 177111	45.75	49	0.14	0.64	0.64	36	85	31
ICMX 1871003	43.98	56	0.22	-0.79	0.80	47	103	43
ICMX 1871018	37.68	107	-0.55	-0.76	0.86	55	162	94
ICMX 1871023	43.63	62	0.67	-0.66	0.95	59	121	59
ICMX 1871027	43.84	59	-0.63	-0.12	3.19	99	158	93
ICMX 1871032	46.52	41	-0.23	-0.71	0.71	42	83	30
ICMX 1871037	54.94	13	0.45	0.07	2.87	96	109	48
ICMX 1871048	56.65	10	-2.14	0.87	5.32	102	112	52
ICMX 1871049	50.21	22	0.16	-0.91	0.91	57	79	28
ICMX 1871050	62.79	3	-0.85	1.18	1.33	75	78	26
ICMX 187760	45.74	50	-0.58	0.21	1.57	82	132	77
ICMX 187762	48.70	30	0.94	0.22	4.12	101	131	74
ICMX 187763	49.26	28	0.20	-0.32	0.34	17	45	10
ICMX 187765	54.64	15	0.49	0.26	0.97	61	76	24
ICMX 187766	50.14	23	0.94	-0.15	5.92	104	127	67
ICMX 187769	57.50	8	-1.09	-1.83	1.94	86	94	39
ICMX 187772	54.76	14	0.23	0.19	0.34	16	30	3
ICMX 187773	45.62	51	-0.21	-0.60	0.60	34	85	32
ICMX 187775	46.67	40	-1.71	-0.30	9.73	108	148	88
ICMX 187778	44.00	55	-1.08	-0.62	2.00	87	142	81
ICMX 187781	58.77	6	-0.56	-0.94	1.00	62	68	18
ICMX 187786	53.61	16	-1.60	-1.03	2.69	93	109	49
ICMX 187788	47.47	33	-0.25	-0.45	0.47	23	56	14

Table 22. Ranking of genotypes based on grain Fe content, AMMI stability value (ASV) and Fe stability index (FeSI) across Sadore, Gampela and Cinzana.

Genotypes	Mea n	Mean rank (A)	IPCA 1	IPCA 2	ASV	AVS rank (B)	FeSI (A+B)	FeSI rank
ICMX 187803	45.90	47	1.58	-0.43	5.83	103	150	89
ICMX 187806	43.92	58	0.07	-0.05	0.10	2	60	15
ICMX 187807	42.31	71	0.11	-0.14	0.16	5	76	25
ICMX 187808	39.02	98	-0.13	0.05	0.35	18	116	54
ICMX 187826	37.46	109	-0.50	-0.21	1.20	72	181	108
ICMX 187827	45.92	46	0.27	-0.31	0.39	22	68	19
ICMX 187829	43.67	61	0.76	1.00	1.15	69	130	72
ICMX 187830	46.45	43	-0.29	-0.55	0.57	31	74	22
ICMX 187832	38.06	102	0.50	0.18	1.42	78	180	106
ICMX 187853	42.40	67	0.54	0.03	11.2 0	110	177	104
ICMX 187854	40.91	82	0.66	-0.06	7.32	105	187	111
ICMX 187856	47.91	32	1.00	0.55	1.91	85	117	55
ICMX 187857	43.97	57	0.19	0.17	0.27	11	68	20
ICMX 187859	41.17	77	0.09	-0.11	0.13	4	81	29
ICMX 187860	42.32	70	-0.65	0.78	0.95	58	128	70
ICMX 187861	49.72	25	-0.11	0.26	0.26	10	35	7
ICMX 187862	46.51	42	0.48	-0.07	3.30	100	142	82
ICMX 187864	43.26	63	0.57	-0.95	1.01	63	126	66
ICMX 187865	47.33	34	0.45	-0.60	0.69	40	74	23
ICMX 187867	40.87	83	0.02	0.00	0.77	44	127	68
ICMX 187868	53.58	17	0.22	0.19	0.32	15	32	5
ICMX 187870	52.12	19	0.22	0.13	0.39	21	40	8
ICMX 187872	42.12	72	0.12	0.04	0.39	20	92	35
ICMX 187875	42.32	69	0.40	-0.44	0.57	32	101	40
ICMX 187876	45.12	52	0.34	0.67	0.69	41	93	37
ICMX 187877	40.83	84	0.83	0.72	1.20	71	155	92
ICMX 187878	46.89	39	0.21	0.67	0.67	39	78	27
ICMX 187880	40.27	88	-0.19	0.24	0.28	13	101	41

Table 22. Ranking of genotypes based on grain Fe content, AMMI stability value (ASV) and Fe stability index (FeSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA 1	IPCA 2	ASV	AVS rank (B)	FeSI (A+B)	FeSI rank
ICMX 187881	41.87	73	0.51	0.35	0.81	50	123	62
ICMX 187882	43.13	64	-0.16	0.79	0.79	46	110	51
ICMX 187883	46.29	45	-0.14	0.52	0.53	27	72	21
ICMX 187885	47.21	36	-0.82	0.24	2.82	95	131	75
ICMX 187889	35.83	111	0.25	0.84	0.84	52	163	95
ICMX 187891	56.41	11	-1.17	-0.10	13.77	111	122	61
ICMX 187892	52.33	18	0.37	0.38	0.53	28	46	11
ICMX 187893	46.95	38	0.61	1.24	1.28	74	112	53
ICMX 187895	49.46	27	-0.08	0.10	0.11	3	30	4
ICMX 187897	54.97	12	-1.67	-0.08	36.70	112	124	64
ICMX 187989	49.25	29	-0.02	-1.44	1.44	79	108	45
ICMX 187995	40.93	81	-0.81	-0.24	2.71	94	175	102
ICMH 177016	48.53	31	0.28	0.54	0.56	29	60	16
ICMH 177017	46.42	44	-1.50	0.77	3.01	98	142	83
ICMH 177018	42.78	66	-0.26	-1.13	1.13	67	133	78
ICMH 177019	49.52	26	0.17	0.15	0.24	8	34	6
ICMH 177020	47.13	37	0.53	-0.14	2.00	88	125	65
ICMH 177023	44.70	53	0.79	-1.32	1.40	77	130	73
ICMH IS 16027	41.29	75	-0.48	0.31	0.80	48	123	63
ICMH IS 16037	39.34	95	0.10	0.48	0.48	24	119	57
ICMH IS 16038	39.28	97	-0.41	1.23	1.24	73	170	100
ICMH IS 16040	37.86	106	0.94	0.77	1.38	76	182	109
ICMH IS 16044	40.59	86	-0.81	-0.32	2.06	89	175	103
ICMH IS 16052	40.03	91	-0.62	0.75	0.91	56	147	87
ICMH IS 16075	40.57	87	0.30	-0.05	1.66	83	170	101
ICMH IS 16076	40.68	85	-0.17	-0.18	0.24	7	92	36
ICMH IS 16120	44.57	54	0.16	-1.02	1.02	64	118	56
ICMH IS 16187	39.80	92	0.02	0.04	0.04	1	93	38

Table 22. Ranking of genotypes based on grain Fe content, AMMI stability value (ASV) and Fe stability index (FeSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA 1	IPCA 2	ASV	AVS rank (B)	FeSI (A+B)	FeSI rank
ICMH IS 16214	42.91	65	0.24	-0.75	0.75	43	108	46
ICMX 187001	50.68	20	-0.03	0.57	0.57	30	50	12
ICMX 187011	37.63	108	-0.21	-0.51	0.52	26	134	79
ICMX 187018	47.25	35	0.67	-0.06	8.13	107	142	84
ICMX 187020	37.93	104	0.17	1.03	1.03	65	169	96
ICMX 187023	41.15	78	0.57	-0.68	0.83	51	129	71
ICMX 187026	58.03	7	0.21	0.19	0.29	14	21	1
ICMX 187031	38.40	100	-0.27	0.29	0.38	19	119	58
ICMX 187040	38.53	99	0.02	1.16	1.16	70	169	97
ICMX 187041	50.37	21	0.37	-0.52	0.59	33	54	13
ICMX 187042	40.17	90	0.48	0.29	0.85	54	144	85
ICMX 187046	57.12	9	0.19	0.16	0.28	12	21	2
ICMX 187048	38.12	101	-0.71	0.17	2.94	97	198	112
ICMX 187050	40.25	89	-0.37	1.45	1.45	80	169	98
ICMX 187054	42.37	68	0.33	0.13	0.84	53	121	60
ICMX 187068	43.72	60	0.89	-0.32	2.45	91	151	91
ICMX 1871038	37.16	110	0.73	-1.01	1.14	68	178	105
ICMX 1871039	39.32	96	0.11	-0.24	0.24	9	105	44
ICMX 1871040	37.97	103	-0.34	-1.03	1.04	66	169	99
ICMX 1871041	41.42	74	2.12	-0.61	7.41	106	180	107
ICMX 1871042	41.22	76	0.30	-0.48	0.52	25	101	42
ICMX 1871043	39.42	94	-0.46	-0.46	0.65	37	131	76
ICMX 1871044	39.70	93	-0.89	0.32	2.49	92	185	110
ICMX 1871045	59.12	5	0.34	-1.49	1.49	81	86	33
ICMX 187572	49.92	24	1.19	1.32	1.70	84	108	47
ICMX 187848	41.05	80	-0.05	0.22	0.22	6	86	34
CHAKTI (C1)	59.51	4	0.16	0.04	0.66	38	42	9
ICMV 167005 (C2)	37.89	105	0.56	0.57	0.79	45	150	90

C1: check 1 and C2: check 2

Table 23. Ranking of genotypes based on grain Zn content, AMMI stability value (ASV) and Zn stability index (ZnSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	ZnSI (A+B)	ZnSI rank
ICMH 1201	52.33	2	-2.32	-0.43	12.58	110	112	49
ICMH 1301	50.21	6	-0.95	0.09	10.16	109	115	53
ICMH 157222	35.95	77	-0.43	0.57	0.65	29	106	45
ICMH 177002	31.95	109	-0.62	0.52	0.91	51	160	97
ICMH 177022	40.72	30	0.70	0.72	0.99	56	86	32
ICMH 177111	38.56	50	0.28	0.70	0.70	33	83	29
ICMX 1871003	37.44	65	0.61	-0.22	1.77	81	146	89
ICMX 1871018	33.59	99	0.81	-0.41	1.62	79	178	105
ICMX 1871023	39.88	39	-0.05	-0.83	0.83	40	79	28
ICMX 1871027	38.68	47	1.07	0.28	4.05	95	142	82
ICMX 1871032	42.68	22	0.96	-0.49	1.96	85	107	46
ICMX 1871037	46.80	11	-0.09	-0.11	0.13	3	14	1
ICMX 1871048	45.05	13	-1.00	1.42	1.58	78	91	35
ICMX 1871049	44.60	15	-0.09	-1.13	1.13	60	75	25
ICMX 1871050	47.85	7	-0.77	0.82	1.10	59	66	20
ICMX 187760	41.45	28	0.24	0.38	0.41	13	41	6
ICMX 187762	37.49	64	0.39	0.32	0.58	21	85	30
ICMX 187763	42.31	24	0.89	-0.12	6.80	103	127	72
ICMX 187765	47.08	9	-0.61	-0.54	0.88	44	53	11
ICMX 187766	43.28	21	0.09	0.25	0.25	7	28	3
ICMX 187769	43.98	19	0.77	-0.10	6.05	100	119	59
ICMX 187772	47.57	8	-0.49	0.18	1.33	69	77	27
ICMX 187773	36.17	74	-1.28	-0.77	2.28	89	163	98
ICMX 187775	39.35	42	0.17	0.23	0.26	8	50	8
ICMX 187778	38.23	56	-0.05	0.10	0.10	1	57	14
ICMX 187781	44.82	14	-0.49	0.28	0.91	50	64	17
ICMX 187786	42.48	23	-0.67	-0.13	3.43	93	116	55
ICMX 187788	38.73	46	0.06	0.27	0.27	9	55	13

Table 23. Ranking of genotypes based on grain Zn content, AMMI stability value (ASV) and Zn stability index (ZnSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	ZnSI (A+B)	ZnSI rank
ICMX 187803	37.23	66	-0.43	-0.58	0.66	31	97	37
ICMX 187806	34.29	90	1.25	0.17	9.29	108	198	109
ICMX 187807	37.07	67	0.28	0.10	0.77	36	103	42
ICMX 187808	32.18	108	0.07	-0.73	0.73	34	142	83
ICMX 187826	32.53	106	0.64	0.10	4.22	97	203	112
ICMX 187827	38.42	53	0.62	0.15	2.55	90	143	86
ICMX 187829	33.98	93	-0.46	0.47	0.64	28	121	65
ICMX 187830	38.59	49	0.94	1.32	1.48	74	123	68
ICMX 187832	33.83	95	-0.22	-0.09	0.54	19	114	50
ICMX 187853	36.44	72	-0.48	-0.03	7.10	104	176	102
ICMX 187854	35.00	85	-0.54	-1.01	1.05	58	143	87
ICMX 187856	39.17	44	-0.42	0.37	0.61	24	68	21
ICMX 187857	38.13	57	0.78	-0.47	1.37	72	129	74
ICMX 187859	37.64	63	0.09	-0.35	0.35	11	74	24
ICMX 187860	39.92	37	-0.27	0.96	0.96	55	92	36
ICMX 187861	40.08	35	0.36	-0.05	2.59	91	126	70
ICMX 187862	40.18	34	-1.02	0.47	2.25	88	122	67
ICMX 187864	38.26	55	0.35	-0.14	0.86	43	98	38
ICMX 187865	40.36	32	0.78	0.09	6.63	102	134	80
ICMX 187867	33.38	101	0.64	-0.14	2.94	92	193	108
ICMX 187868	44.59	16	-0.84	0.15	4.68	99	115	54
ICMX 187870	46.47	12	-0.29	-1.20	1.20	64	76	26
ICMX 187872	38.88	45	0.09	0.01	1.54	76	121	66
ICMX 187875	31.57	112	0.06	0.44	0.44	15	127	73
ICMX 187876	35.78	78	-0.62	-0.29	1.36	71	149	90
ICMX 187877	36.05	76	-0.59	-0.30	1.23	66	142	84
ICMX 187878	38.67	48	-0.67	-0.02	29.09	111	159	96
ICMX 187880	38.08	58	-0.05	0.24	0.24	6	64	18

Table 23. Ranking of genotypes based on grain Zn content, AMMI stability value (ASV) and Zn stability index (ZnSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	ZnSI (A+B)	ZnSI rank
ICMX 187881	38.43	52	-0.65	-0.62	0.91	52	104	43
ICMX 187882	39.88	38	-0.50	0.29	0.90	47	85	31
ICMX 187883	40.28	33	0.55	0.15	2.06	86	119	60
ICMX 187885	38.03	60	2.09	0.01	514.63	112	172	100
ICMX 187889	36.12	75	1.05	0.85	1.55	77	152	92
ICMX 187891	35.21	82	-0.55	0.37	0.90	48	130	76
ICMX 187892	39.32	43	0.48	-0.03	8.31	107	150	91
ICMX 187893	36.91	69	-0.36	0.30	0.53	18	87	34
ICMX 187895	44.26	18	-0.40	0.51	0.60	23	41	7
ICMX 187897	40.48	31	0.47	-0.44	0.66	32	63	16
ICMX 187989	41.89	26	1.61	-0.35	7.41	105	131	78
ICMX 187995	35.43	80	0.64	0.10	4.09	96	176	103
ICMH 177016	43.56	20	0.02	-0.15	0.15	4	24	2
ICMH 177017	41.78	27	0.07	1.80	1.80	82	109	47
ICMH 177018	38.46	51	0.92	-0.60	1.53	75	126	71
ICMH 177019	41.18	29	0.41	-0.34	0.60	22	51	10
ICMH 177020	42.18	25	0.79	0.16	3.89	94	119	61
ICMH 177023	39.63	41	0.79	-0.89	1.14	61	102	40
ICMH IS 16027	34.76	87	-0.20	0.64	0.64	27	114	51
ICMH IS 16037	32.78	105	0.00	0.38	0.38	12	117	56
ICMH IS 16038	31.79	110	-0.92	0.84	1.32	67	177	104
ICMH IS 16040	33.69	98	-1.07	0.18	6.46	101	199	110
ICMH IS 16044	36.18	73	0.40	0.19	0.84	41	114	52
ICMH IS 16052	36.70	71	0.07	1.34	1.34	70	141	81
ICMH IS 16075	36.98	68	0.01	-0.24	0.24	5	73	23
ICMH IS 16076	34.17	91	-0.17	0.58	0.58	20	111	48
ICMH IS 16120	40.04	36	0.49	-0.37	0.75	35	71	22
ICMH IS 16187	35.17	83	-0.34	-0.08	1.46	73	156	94

Table 23. Ranking of genotypes based on grain Zn content, AMMI stability value (ASV) and Zn stability index (ZnSI) across Sadore, Gampela and Cinzana.

Genotypes	Mean	Mean rank (A)	IPCA1	IPCA2	ASV	AVS rank (B)	ZnSI (A+B)	ZnSI rank
ICMH IS 16214	38.06	59	0.31	-0.11	0.89	46	105	44
ICMX 187001	44.38	17	0.22	0.47	0.49	16	33	4
ICMX 187011	33.84	94	0.43	-0.49	0.62	25	119	62
ICMX 187018	39.70	40	0.17	-0.43	0.44	14	54	12
ICMX 187020	31.57	111	-0.45	0.18	1.16	62	173	101
ICMX 187023	37.65	62	-0.37	-0.80	0.82	38	100	39
ICMX 187026	50.97	4	-0.87	0.16	4.64	98	102	41
ICMX 187031	33.21	102	0.23	0.49	0.50	17	119	63
ICMX 187040	33.53	100	-0.45	0.80	0.84	42	142	85
ICMX 187041	46.88	10	-0.10	-0.62	0.62	26	36	5
ICMX 187042	33.12	103	-0.25	-0.65	0.66	30	133	79
ICMX 187046	53.26	1	-0.73	-0.50	1.19	63	64	19
ICMX 187048	32.44	107	0.15	-0.07	0.33	10	117	57
ICMX 187050	34.99	86	-0.61	0.98	1.05	57	143	88
ICMX 187054	37.93	61	-0.68	-0.36	1.32	68	129	75
ICMX 187068	38.28	54	-0.16	-1.20	1.20	65	119	64
ICMX 1871038	32.87	104	0.46	-0.91	0.94	53	157	95
ICMX 1871039	34.53	88	0.05	-0.78	0.78	37	125	69
ICMX 1871040	33.98	92	0.97	-0.44	2.19	87	179	106
ICMX 1871041	36.75	70	-0.70	-1.86	1.88	84	154	93
ICMX 1871042	35.13	84	0.04	0.11	0.11	2	86	33
ICMX 1871043	34.36	89	0.68	0.28	1.66	80	169	99
ICMX 1871044	35.21	81	0.61	0.48	0.91	49	130	77
ICMX 1871045	50.73	5	-0.42	-0.86	0.88	45	50	9
ICMX 187572	35.65	79	-0.47	-0.77	0.82	39	118	58
ICMX 187848	33.70	97	0.36	-0.07	1.82	83	180	107
CHAKTI (C1)	52.23	3	-0.60	0.84	0.94	54	57	15
ICMV 167005 (C2)	33.78	96	-0.66	0.06	7.46	106	202	111

C1: check 1 and C2: check 2

The G×E interaction was further partitioned into IPCA 1 and IPCA 2, of which the figure (4) gives the AMMI biplot for grain yield. The IPCA1 component accounted for 68.01 % of G×L interaction, while IPCA 2 accounted for only 31.99 %. Distribution of genotype points in the AMMI biplot revealed many genotypes scattered close to the origin, indicating minimal interaction of these genotypes with environments.

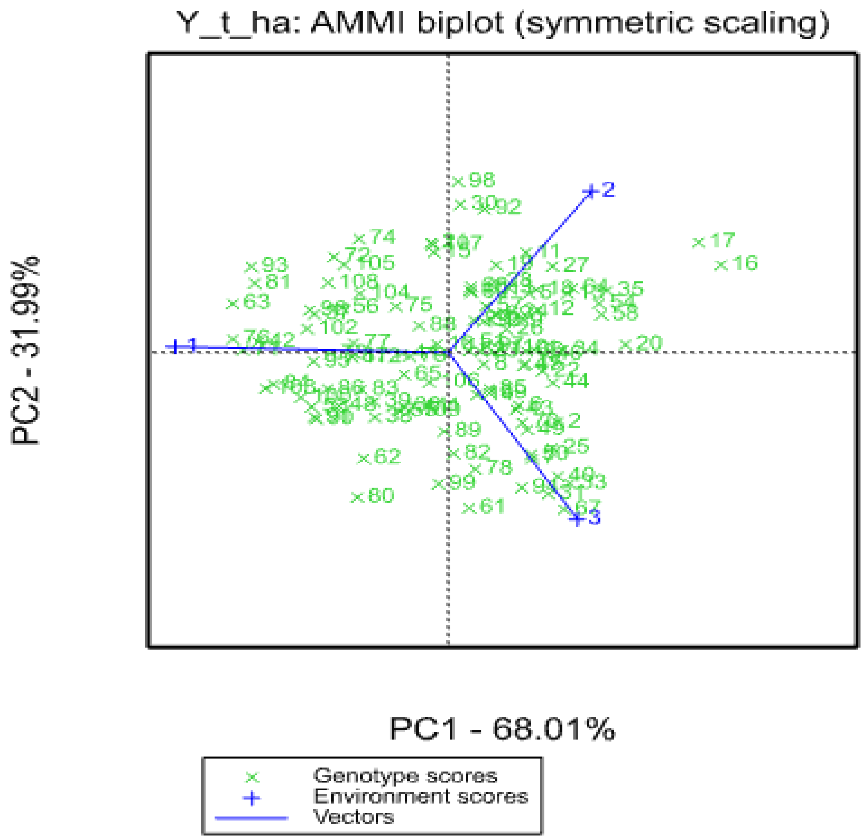

Figure 4. AMMI-biplot showing patern of adaptability and stability of 110 hybrids of pearl millet together with two checks cultivars at Sadore, Gampela and Cinzana for grain yield (t/ha)

Figure (5) gives the AMMI biplot for grain Fe content. The IPCA1 component accounted for 54.34 % of G×L interaction, while IPCA 2 accounted for 45.66 %. Distribution of genotype points in the AMMI biplot revealed also many genotypes scattered close to the origin, indicating minimal interaction of these genotypes with environments.

The scatter of the genotype points in the AMMI biplot showed many groups of genotypes close to the origin in the biplot for grain Zn content (Figure 6). The IPCA1 component accounted for 60.19 % of G×L interaction, while IPCA 2 accounted for 39.81 %.

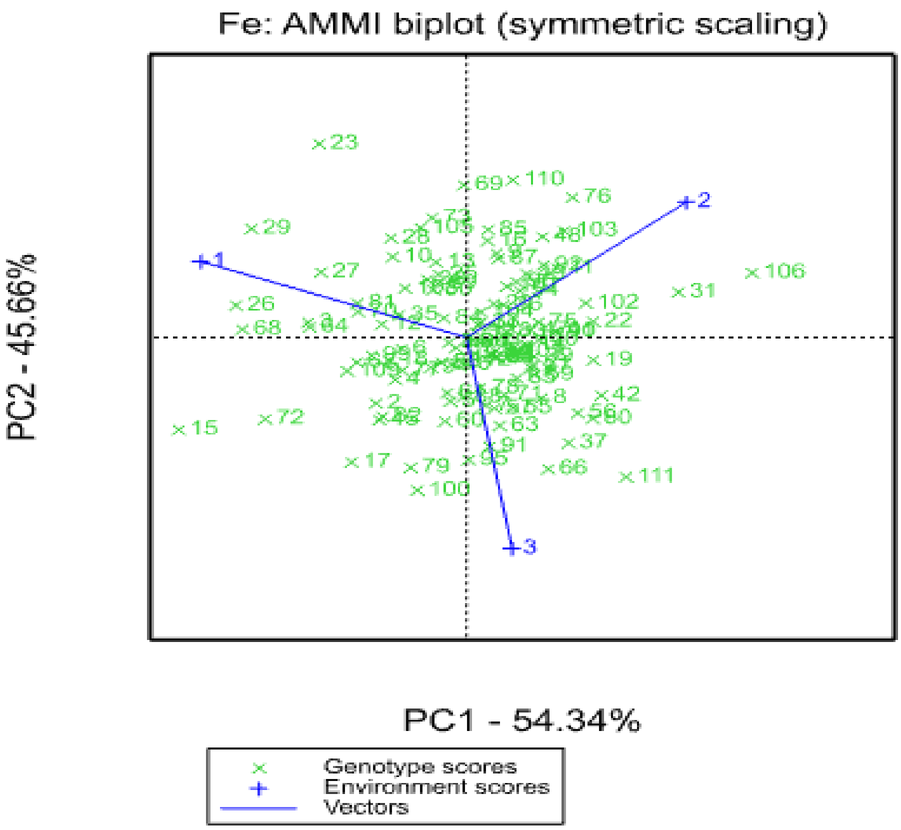

Figure 5. AMMI-biplot showing pattern of adaptability and stability of 110 hybrids of pearl millet together with two checks cultivars at Sadore, Gampela and Cinzana

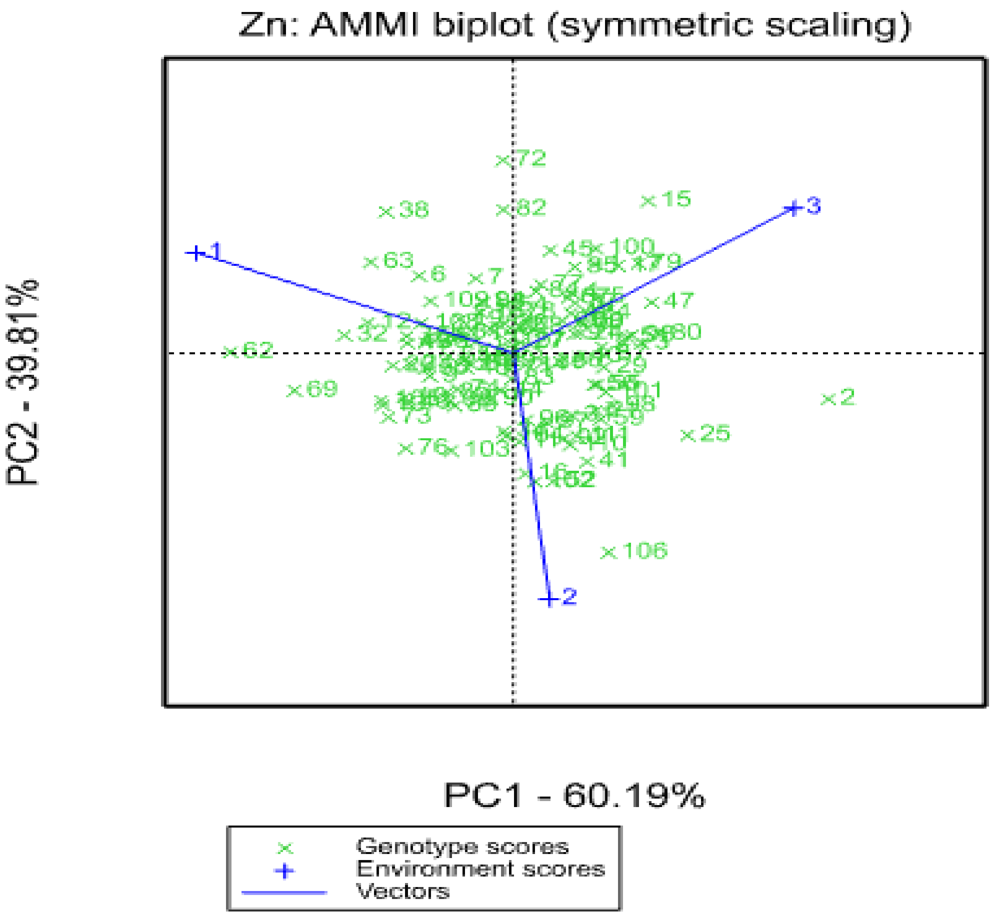

Figure 6. AMMI-biplot showing pattern of adaptability and stability of 110 hybrids of pearl millet together with two checks cultivars at Sadore, Gampela and Cinzana

CHAPTER IV: DISCUSSION

4.1. Combining Ability and Heterosis for Agronomic Traits and Grain Quality in Pearl Millet (*Pennisetum glaucum* L.) for Hybrid Breeding in West Africa.

Pearl millet is an important crop of smallholder farmers of West Africa. It is climate resilient and nutritious food crop. But, the grain yields in the farmers' fields are limited because of usage of non-productive cultivars with lower micronutrient concentration. This can be addressed by breeding high yielding, biofortified hybrids with wide adptability. Analysis of variance of line × tester material across environments indicated presence of significant variability among the test material used in the present study and can be exploited though selection. The wide range of mean for all traits and the different proportional contribution of lines, testers and their interaction to total variance of each trait across environments provides consolidated evidence of the presence of sufficient genetic variability among lines, testers, and hybrids. Singh *et al.* (1974), Singh and Sharma. (2014), Patel *et al.* (2016) and Kumawat *et al.* (2019) reported also significant genetic variations in pearl millet. Regarding the proportional contribution, similar results were also reported in pearl millet for number of days to 50% flowering, plant height and panicle circumference by Kumar *et al.* (2017) and Badurkar *et al.* (2018) and by Govindaraj *et al.* (2013) for grain Fe and Zn content. These significant levels of genetic variability observed for all traits in the present study suggested a good potential for improvement of target traits since it offers scope for selection to tailor genotypes to better suit diverse agro-ecological conditions. It also provides raw material for breeding hybrids better able to cope with biotic and abiotic stresses. Moreover, this genetic diversity is useful for an efficient selection method for the fixation of desirable genetic combinations to increase the success and diversity of hybrid breeding program.

The individual analysis of variance indicated absence of significance effects for female × male on panicle length and grain yield only at Gampela and for grain Zn content at Sadore content, indicated that the two environments are different as well as the effect of environment in the parents and hybrids expression as reported in pearl millet (Pawar *et al.,* 2018; Anuradha *et al.,* 2017; Pucher *et al.,* 2014; Bashir *et al.,* 2013), Sorghum (Phuke *et al.,* 2017) and Wheat (Badakhshan *et al.,* 2013). The difference of environment even gotten the support from the grain Fe and Zn content which indicated no significant and the panicle length that indicated the preponderance of additive component both at Gampela and the preponderance of non-additive component at Sadore. Importantly, this difference of environment is a prerequisite to set the real performance of parents and hybrids whereas, the difference in the expression and magnitude is useful for their adaptability and stability assessment. Then the hybrids showed means greater than the overall mean across locations for considered trait had some adaptability for this trait. Whereas, the hybrids with similar performance across locations were considered as the stable's ones. Mean sum of squares of the remining trait were found significant in the interaction of female × male, indicated the presence of the interaction effect on these traits as reported by Sattler *et al.* (2019). Due to the presence of significance effects of hybrids for all traits, the preponderance of hybrids expressions in the inheritance of these traits was involved. Also, the few number of hybrids which showed desirable performance specially for grain Fe and Zn content across locations, indicated the presence of environment effects on these micronutrients. Earlier studies in pearl millet (Pawar *et al.,* 2018; Anuradha *et al.,* 2017; Pucher *et al.,* 2014; Bashir *et al.,* 2013; Govindaraj *et al.,* 2013) in Sorghum (Phuke *et al.,* 2017) and Wheat (Badakhshan *et al.,* 2013) observed these micronutrients to be largely affected by numerous environmental conditions.

Combining ability studies revealed that both sigma square of general and specific combining ability was important, indicated the importance of both additive and non-additive components in the inheritance of traits study in the present investigation. Similar observations have been reported by Kumawat *et al.* (2019) and Sattler *et al.* (2019). The magnitude of sigma square of GCA was higher as compared to magnitude of sigma square of SCA for number of days to 50% flowering, plant height and panicle circumference across locations which indicated the preponderance of additive components for these traits across locations. These observations confirm the statements of Melchinger and Gumber. (1998), Technow *et al.* (2014) and Schrag *et al.* (2018) who's already supported additive components to be more common in single-cross hybrids belonging to distinct heterotic groups. Because, a large genetic distance between the parents is supposed to increase the predictability ratio, since additive variance becomes more important relative to nonadditive variance (Sattler *et al.,* 2019). The predominance of additive gene action for number of days to 50% flowering, plant height and panicle circumference would make recurrent selection for intra-population improvement and open–pollinated variety (OPV) development highly effective (Govindaraj *et al.,* 2013; Kanatti *et al.,* 2014). Such type of gene actions clearly indicated also that selection of superior plant in terms of earliest (50% flowering), plant high and panicle circumference must be postponed to later generation, where these traits could be improved by making selections among the recombinants within the segregating population. Contrary, the magnitude of sigma square of GCA was lower as compared to magnitude of sigma square of SCA for grain yield, grain Fe and Zn content across location, which indicated the preponderance of non-additive components for these traits across locations. The additive sigma square higher than the dominance sigma square associated with high predictability ratio consolidated that the number of days to 50% flowering, plant height, and panicle circumference were under additive genetic control. These findings collaborate with the finding of Pucher *et al.* (2016), Singh and Sharma. (2014) in pearl millet. By other hand, the higher dominance sigma square over the additive sigma square associated with low predictability ratio for grain yield, grain Fe and Zn content across locations consolidated that the underlying physiological processes determining grain yield, grain Fe and Zn were largely under dominance control, making hybrids breeding highly effective. These funding were in agreement with the funding of Arulselvi *et al*. (2006) that observed grain Fe and Zn content to be under dominance genetic control and Singh and Sharma. (2014) and Pucher *et al.* (2016) who 's observed grain yield to be largely under dominant genetic control in pearl millet. Such type of gene actions indicated that selection of superior plant in terms of grain yield, grain Fe and Zn content, can be obtained just at the first generation, which is one of goal in high biofortified F_1 hybrids breeding. Because it enables selection of parental lines based on their offspring's GCA (Melchinger *et al.,* 1987). In addition, the obtention of high yielding hybrids with high grain Fe and Zn content at the first generation reduce the breeding time and is important to keep pace with climate change and cushion pearl millet farmers from its impact and contribute to food and nutrition security.

Unexpectedly, highly significant and positive correlations between performance *per se* of the hybrids and mid-parental values for grain Fe and Zn content was found, indicated these micronutrients to be under additive genetic control. Similar results in pearl millet have been reported in earlier studies (Velu *et al.,* 2011; Govindaraj *et al.,* 2013; Kanatti *et al.,* 2014). This observation, indicated that in addition to the advantage to be taken at the first generation, the improvement of grain Fe and Zn content requires late testing of specific combinations to cover dominance effects. Thus, early testing will not lead certainly to a desired outcome of grain Fe and Zn content and call for recurrent selection among the recombinants segregating population.

An overall appraisal of GCA did not identified any line or tester that combining all the traits, which suggested breeding for these traits would be effective when material is tested in a wide range of environments. Similar results in pearl millet have been reported by Kumawat *et al.* (2019). However, some lines and testers that combine good for more than one trait across locations have been identified and are useful for breeding hybrids for multiple purpose as looking by West Africa pearl millet farmers. Singh *et al.* (1974) reported also lines and testers that combined good for more than one trait on some seven quantitative traits. The rest of lines and testers were good general combiners each either for one, either in one location or for any trait. Hence, there lines and testers showing good general combining ability for particular traits in particular location may be utilized in component breeding programme for improving specific trait of interest. The parents which are good general combiners for more than one character were considered as the potential parents for hybrids breeding and could be utilized in further breeding programme in order to combine more characters by involving fewer numbers of parents in a crossing programme. The parents exhibiting good GCA for particular trait were also having desirable *per se* performance contribute either additive gene effect or additive x additive interaction effect, can be considered as a reliable criterion for selecting parents for hybridization as suggested by Mungra *et al.* (2015). The non-significance of GCA effects for parents for some traits show that they had little contribution to additive gene action of the trait. While, the negative significant GCA estimates, recorded by parents suggests, that the genotypes had low gene frequencies for the trait as reported by Owusu *et al.* (2018), thereby making them undesirable for the genetic improvement of their traits (Daniel *et al.*, 2006; Ayo-Vaughan *et al.*, 2013). The variable GCA estimates observed in the parents for nearly all the traits points to the existence of positive and negative (dominant and recessive) alleles among the parents leading to different levels of expression of the traits (Azad *et al.*, 2014; Owusu *et al.*, 2018).

Although in the best hybrid combinations, it was not always both parents which were the best general combiners, in almost all the good combinations at least one good general combiner was involved. This was particularly so when the *per se* performance was considered. Similar results in pearl millet have been reported in earlier studies (Singh *et al.,* 1974; Singh and Sharma, 2014). While, Govindaraj *et al.* (2013) and Velu *et al.* (2011) reported, involved of both parental lines having high levels of Fe and Zn for breeding hybrids with high Fe and Zn density. The high performance of such combinations as high × high and high × low general combiners indicates more additive × additive types of gene-interaction, whereas a few hybrids with low × low general combiners show non-additive types of epistatic interaction. Similar type of gene-interactions has been reported in pearl millet by Singh *et al.* (1974) and Mungra *et al.* (2015). Suggested the recurrent selection followed by pedigree or biparental mating or diallel selective mating systems to be effective in desirables characters improvement. As well, all the best hybrid combinations in the present study involving good × good and poor × poor general combiners parents could be attributed to the complementation between favourable alleles of the parents involved as suggested by Raut *et al.* (2017).

Undoubtedly, the high SCA effects denote, a high heterotic response, but this may be due to the very poor performance of the parents in comparison with their hybrids, the selection of cross combinations on the basis of *per se* performance would be more realistic. Thereby, many hybrids across locations showed heterosis in the desirable sense over the mid parent as well as over better parental of the trait considering. In an earlier pearl millet study, Ouendeba *et al.* (1993), Patel *et al.* (2016), Acharya *et al*. (2017), and Sattler *et al.* (2019) reported similar heterosis for grain yield and related traits whereas, Velu *et al.* (2011), Govindaraj *et al.* (2013) and Kanatti *et al.* (2014) reported heterosis only over mid parent for grain Fe and Zn. This could be due to the high grain Fe and Zn parents used during their trials. The heterosis over the mid-parent and better-parent for grain yield, grain Fe and Zn content observed in the present study, further supports the fact that the processes determining their traits were largely under dominance genetic control. Hybrids showed heterosis in desirable sense for specific location would show some adaptation to this environment. Because heterosis in hybrid has been reported to be more pronounced in its area of adaptation (Shull, 1914).

The earliness of hybrids observed in the trial across location is useful in the Sahelian context of West Africa where the rainy season is no longer than 3 months. Whereas, the positive heterosis for plant height is desirable in West Africa because pearl in this region is growing for multiple purpose. Also, in West Africa the panicle characteristics had similar importance as grain yield, then the positive heterosis for panicle length, panicle circumference as well as grain yield are desirable especially for pearl millet extension in the region. Specially where the general expectation of the pearl millet farmers is mainly focused on level of superiority of newly released hybrids than the local standard cultivar grown across the region (Pucher *et al.*, 2015).

There were highly significant and positive correlations between all the traits of the parental lines and testers *per se* and their GCA across locations, indicating that suitable general combiners may be selected on the basis of mean performance itself. Thus, it would imply that, as compared to breeding lines and testers with low traits, lines and testers selected for their high traits are more likely to include those with high GCA for these traits. An earlier pearl millet study also reported a highly significant and positive correlation between performance *per se* of the inbred lines and their GCA for days to 50% flowering, plant height, panicle length, panicle circumference, grain yield (Singh and Sharma, 2014; Mungra *et al.*, 2015) and for grain Fe and Zn content (Velu *et al.*, 2011; Rai *et al.*, 2012 Govindaraj *et al.*, 2013; Kanatti *et al.*, 2014). Similarly, there were highly significant and positive association between the hybrids *per se* and their SCA in both trials, indicating that effective selection for simultaneous genetic improvement of performance *per se* of hybrids and their SCA would be possible in pearl millet. Then a multi-locational testing would identify their suitability for all traits studied. Similar association between the hybrids *per se* and their SCA for yield and its attributing characters have also been reported by Kumawat *et al.* (2019) and by Govindaraj *et al.* (2013) and Kanatti *et al.* (2014) for grain Fe and Zn content.

Regarding, the correlation among traits, there were highly significant and positive correlations between grain Fe and Zn content in the parental lines as well as in the hybrids. Several studies in pearl millet (Bashir *et al.,* 2013; Govindaraj *et al.*, 2013; Kanatti *et al.*, 2014; Pucher *et al.,* 2016; Acharya *et al.,* 2017) and other cereals, such as sorghum (Phuke *et al.,* 2017), maize (Oikeh *et al.,* 2004), rice (Anandan *et al.,* 2011) and wheat (Badakhshan *et al.,* 2013) have also reported highly significant and positive correlations between these two micronutrients. This would imply an implication for the possibility of combine simultaneous selection for these micronutrients in a single agronomic background. However, there micronutrients were negatively associated with grain yield, indicated that proper selection should be taken when hight yielding hybrids with high grain Fe and Zn content became the breeding target. Negative correlations between grain yield and grain Fe and Zn content has been earlier reported by Rai *et al.* (2012) and Yadav *et al.* (2016) in pearl millet and by Reddy *et al.* (2010) in sorghum. This negative association can be improved though identification of high yield and high Fe and Zn QTL and pyramiding them in the parental lines using marker-assisted selection (Yadav and Rai, 2013). Plant height and panicle length exhibited significant and positive correlation with grain yield. This would imply likely effectiveness of simultaneous selection for plant height, panicle length and grain yield, which is very important for breeding the farmer desirable hybrids in West Africa. Similar association has been reported in hybrids by Sumathi *et al.* (2017).

4.2. Improvement of Restorer Lines for Strengthening Pearl Millet (*Pennisetum glaucum* L.) Hybrid Breeding in West Africa

Results emanating from the restorer's lines improvement study showed extensive genetic variability for all the studied traits among the parents and crosses of pearl millet, indicating presence of significant variability and can be exploited through selection. This variability can be explored for the development of new high yielding restorers with good pollen capacity for desirable hybrid production. Due to the fact that the probability of selecting superior genotypes immensely dependent on the existing genetic diversity in the genotypes, which is also a function of the influence of the additive variance (Ramalho *et al*, 1993). The high variability, suggested a good potential and raw material for restorer's improvement in WCA. The results can also be of broader interest for the WCA pearl millet breeding community, especially the national agriculture research services that initiated hybrid breeding programs and seek for new restorers' parents.

Association of agronomic and morphological traits revealed presence of significant and positive correlation of grain Fe content with grain Zn content. Similar results were reported by Pucher *et al.* (2014), and Govindaraj *et al.* (2013). This showed that the underlying physiological processes determining both micronutrients were largely associated and improvement of one trait can improve the other. This would imply that recurrent selection can be effectively used for intra population improvement of Fe and Zn densities (Govindaraj *et al*, 2013). Plant height, panicle length, and grain yield exhibited significant negative correlation with grain Fe and Zn contents. Similar findings were reported by Kanatti *et al*. (2014). Plant height and panicle length exhibited significant and positive correlation with grain yield and biomass yield. This would imply likely effectiveness of simultaneous selection for plant height, panicle length and grain yield, which is very important for breeding farmer desirable hybrids (Govindaraj *et al*, 2013). Presence of significant GCA and SCA mean squares for traits indicates that both additive and non-additive genetic effects were important in determining these traits as averred by Griffing (1956) and there is the probability of obtaining new varieties (Silva *et al*, 2004). The negative correlations among grain yield and grain Fe and Zn can be improved though identification of high yield and high Fe and Zn QTL and pyramiding them in the parental lines using marker-assisted selection (Govindaraj *et al*, 2013; Yadav and Rai, 2013).

The predominance of GCA mean squares over SCA mean squares and higher magnitude of SCA variance to the GCA variance for the studied traits suggested that, both additive and non-additive gene interactions are important in controlling the inheritance of these traits. These findings are in agreement with Singh J and Sharma R. (2014).

The significant SCA effects and *per se* performance for grain yield displayed by ICMX 1770198, and ICMX 1770199 and high SCA effects and *per se* performance for grain Fe and Zn contents displayed by ICMX 1770197, and ICMX 1770204 further confirm the preponderance of non-additive gene action in these crosses. The high SCA effects of crosses for grain yield, grain Fe and Zn contents might be due to complementation of combining loci

(Raut *et al*, 2017). Parents of these crosses can be used for bi-parental mating or reciprocal recurrent selection for developing superior varieties or hybrids (Azad *et al*, 2014).
Reciprocal effects are important because they can detect a desirable female seed parent base in hybridization program, particularly for producing commercial F1 hybrids. The significance of the reciprocal mean squares for all the studied traits and significance of mean squares of maternal effects for panicle circumference, grain yield and biomass yield indicate proper care should be taken for choosing parents in breeding for improvement of these traits.

The significant and ample genetic variation, as well as sufficiently high narrow sense heritability were observed for most of the traits indicated that, genotype plays a most important role than the environment in determining the phenotype and suggesting predominance of additive gene effects in the inheritance of the studied traits (Govindaraj *et al*, 2011) and the feasibility of restorer improvement, for breeding farmer preferred pearl millet hybrids (Pucher *et al*, 2014). Therefore, progeny performance can be predicted based on the GCA for the traits. Presence of high magnitude of heterosis for most of the studied traits suggested enough diversity among the parental lines. This showed the existence of great potential for improved pearl millet restorers' lines because of the high level of heterosis and genetic diversity observed (Satyavathi *et al*, 2009; Yadav, 2007; Mather K and Jinks JL, 1971; Fonseca S and Patterson FL, 1968). The presence of depicted significant positive heterosis over their mid parent and better parent values for all morphological and agronomic traits studied showed that these traits were most heterotic traits (Kumar *et al*, 2016).

Grain yield is the character and an attribute of economic importance for which considerable positive magnitude of heterosis is needed. Number of crosses was registered considerable magnitude in desirable sense for this trait over MPH and BPH. Such a situation of heterosis in pearl millet has also been reported by Bhasker *et al*. (2017), Nandaniya *et al*. (2016), Chotaliya *et al*. (2009) and Vetriventhan *et al*. (2008). Also, desirable significant positive heterosis was found over MPH and BPH for traits plant height, panicle length, panicle circumference and biomass yield. These characteristics have high value as grain yield for West and Central Africa pearl millet farmers (Pucher *et al*, 2018). Positive significant estimates of MPH and BPH were also recorded by some crosses for grain Fe and Zn content. This further supports the fact that the physiological processes determining Fe and Zn densities in grains were partially under additive genetic control, but it also indicates some degree of over dominance of genes responsible for high Fe and Zn densities over those responsible for low Fe and Zn densities (Govindaraj *et al*, 2013).

4.3. Estimation of standard heterosis for grain yield and grain iron (Fe) and zinc (Zn) content in single and top cross hybrids of pearl millet (*Pennisetum glaucum* (L.) R. Br.) in West Africa.

The pooled analysis of variance showed highly significant differences among the hybrids for all the traits, indicating the presence of considerable amount of variability among the material tested, which is a prerequisite in the establishment of a successful breeding programme based on commercial heterosis (Kanfany *et al,* 2018; Kumar *et al,* 2017; Patel *et al,* 2016). Subi MIM and Idris AE. (2013) also reported high variability in pearl millet that provides remarkable opportunity to improvement pearl millet production though selection. The variance due to location was found to be higher than the variance due to hybrids for all the traits, indicated the high contribution of environment in the variance of the interaction, hybrid x location. Nevertheless, the variation observed is a joint contribution of both genes as well as environment. Earlier studies in pearl millet Misra *et al.* (2009) reported also the influence of environment on these traits whereas Bachir *et al.* (2013) reported the variance of genotypes to be greater than the variance of environment for agro-morphological in pearl millet. The wide ranges for several traits observed in these hybrids of pearl millets in addition underlines the very impressive diversity that exists in the tested hybrids (Govindaraj *et al,* 2011). This wide range of variation observed for all the traits would offer scope of selection desirable genotypes. Earliers studies in pearl millet Patel *et al.* (2016), Pucher *et al.* (2015; 2016) and Bachir *et al.* (2013; 2014), Govindaraj *et al.* (2013) reported similar rang for agro-morphological and grain Fe and Zn content. The observed agro-morphological diversity reflects hybrids of pearl millet's adaptability to a wide range of contrasting environments and it was not a one-size-fits-all hybrids of pearl millet in West Africa (Pucher *et al,* 2015; Hausmann *et al,* 2012). This diversity needs to be tapped and used efficiently in pearl millet production improvement in the context of climate change and to serve well the diversity of needs of smallholder farmers (Pucher *et al,* 2015). Interestedly, all the hybrids tested were predominantly early-to-medium maturity. Then, pearl millet being grown in erratic conditions of rainfall in West Africa, the earliness observed in flowering and maturity are desirable in pearl millet for escaping the shorting period of rainy season (Kumar *et al,* 2017; Arulselvi *et al,* 2006). The present findings corroborate with the findings of Bhasker *et al.* (2017), Kapoor R and Singh P. (2017), Chotaliya *et al.* (2009), Vetriventhan *et al*. (2008) who have also reported earliness of hybrids. In West Africa as in many parts of world, pearl millet is growing as multipurpose crop, then the range of medium to tall observe for plant height in this study is as important as the panicle length and panicle circumference (Kumar *et al,* 2017; Yadav *et al,* 2012) and Pucher *et al.* (2015) reported varied range for these traits in pearl millet in West and Central Africa.

The heterosis for grain yield, grain Fe and Zn measured in terms of superiority over the standards checks (CHakti and ICMV 167005) was valuable. These funding was in agreement with the funding of Badhe *et al.* (2018), Patel *et al.* (2016) and Ati. (2015). Grain yield is the character and an attribute of economic importance (Bhasker *et al,* 2017), for which considerable magnitude of heterosis was registered in a number of hybrids. Earlier studies in pearl millet (Bhasker *et al,* 2017; Nandaniya *et al,* 2016; Vagadiya *et al,* 2010) and in sorghum Taye *et al.* (2016) showed positive heterosis for hybrids over OPVs. In all locations top cross hybrids had more grain yield, higher and longer panicle than single cross hybrids showed their adaptability over single cross hybrids in West Africa, the correlation between these traits. An obviousness, showed positive correlation between plant height, panicle length and grain yield. Earlier studies in pearl millet (Kapoor R and Singh P, 2017) and sorghum (Taye *et al,* 2016) also, found top cross hybrids superior in grain yield and plant height compared to the single cross hybrids. Thus, top cross hybrids match three specific characteristics (plant height, panicle length and grain yield) of needs of pearl millet smallholder farmers in West Africa (Pucher *et al,* 2018).

In addition to grain yield, enhanced micronutrient density of grain should be an additional advantage specially in West Africa due to the height prevalence of micronutrient deficiency in the region (Pucher et al, 2018). Few of hybrids showed positive heterosis for grain Fe and Zn over CHAKTI (the highest OPVs for Fe and Zn) and most of them are single cross hybrids. Badhe *et al.* (2018) and Jethva *et al.* (2012) also reported standard heterosis for grain Fe and Zn content in desirable direction. While, the majority of hybrids had positive heterosis more pronounced in single cross hybrids over ICMV 167005. In confirmation, single cross hybrids showed some earliness than the top cross in both trials and number of days to 50 per cent flowering, was found to have positive correlation with grain Fe (r=0.23) and Zn (r=0.26). Thus, earlier hybrids should have more grain Fe and Zn content but less grain than the late ones. Such a situation of combinational heterosis in late pearl millet has also been reported by Bhasker *et al.* (2017). Also, the grain yield had found to have negative correlation with grain Fe (r=-0.29) and Zn (r=-0.25) leading to the less grain yield and high grain Fe and Zn content of single cross hybrids over top cross hybrids. Then, single cross hybrids of pearl millet present better for pearl millet biofortification in West Africa agroclimatic zone. Positive heterosis in grain Fe and Zn content is reported by Kanatti *et al.* (2014), Govindaraj *et al.* (2013) and Velu *et al.* (2011).

There were positive correlations between grain Fe and Zn densities in both single and top cross hybrids. Several studies in pearl millet (Acharya *et al,* 2017; Nandaniya *et al,* 2016; Pucher et al, 2016; Kanatti et al, 2014; Bashir et al, 2013) and other cereals, such as sorghum (Phuke *et al,* 2017), maize (Oikeh *et al,* 2004), rice (Anandan *et al,* 2011), and wheat (Badakhshan *et al,* 2013), have also reported highly positive correlations between these two micronutrients. This would imply an implication for the possibility of combine simultaneous selection for these micronutrients in a single agronomic background (Govindaraj *et al,* 2013). The negative association observed between traits can be due to the genotype-environment interaction, making these traits less amenable to selection (Farshadfar *et al,* 2011). Then identification of superior genotypes for a range of environments calls for the evaluation of genotypes in many environments to determine their true potential (Yaghotipoor A and Farshadfar E, 2007).

4.4. Assessment of Adaptability and Stability of Hybrids of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) at Sadore, Gampela and Cinzana.

Combined analysis of variance resulted in highly significant differences ($P<0.01$) in the interaction of genotypes × environments for almost all the traits, indicated that the genotypes performed differently across the test environments. Significant differences for genotypes, environments and G × E interaction indicated the effect of environments in the G × E interaction, genetic variability among the entries and possibility of selection for stable genotypes (Farshadfar *et al,* 2011, Lubadde *et al,* 2016). Several studies in pearl millet (Sumathi *et al,* 2017; Pucher *et al,* 2015) and other cereals, such as sorghum (Tack *et al,* 2017), maize (Abuali *et al,* 2014), rice (Bose *et al,* 2014) and wheat (Farshadfar *et al,* 2011; Yan *et al,* 2007) reported also the implication of environment on the expression of traits. This also elucidated the variations in the performance ranks of the genotypes in the different environments (Dixon AD and Nukenine EN, 2000; Malosetti *et al,* 2013). However, as noted by Crossa (1990), ANOVA does not explore the underlying structure within the GEI and thus AMMI model was used.

Analysis of variance carried out to partition the total variances into its components following AMMI model revealed highly significant differences among the genotypes for all the traits as also reported by Subi, MIM and Idris AE. (2013). The highly significant genetic variation and the wide ranges of mean for several traits observed underlines the very impressive diversity in this collection of 110 hybrids, indicated their high capacity to buffer variable environmental conditions (Lubadde *et al,* 2016; Haussmann *et al,* 2012). Moreover, the ranking of the genotypes for grain yield, grain Fe and Zn in the different environments showed wide differences indicating interaction of genotypes with the environments (Misra *et al*, 2009). Similar variations in response to pearl millet to different environments have been reported (Kanfany *et al,* 2018, Sumathi *et al,* 2017). Variation in ranking of genotypes was also reported by Parmar *et al.* (2012) in rice, Mosleh *et al.* (2015) in Weat and Namorato *et al.* (2009) in maize. This sufficient genetic variation for the traits, is a crucial point for improving pearl millet production though hybrid breeding program (Pucher *et al*, 2014). Therefore, this genetic variability offers scope for natural and artificial selection to tailor genotypes to better suit climate variability and change (Bachir *et al*, 2013). Importantly, the Performance *per se* of hybrids response to the desirable performance looking by West Africa pearl millet farmers. Earlier studies in pearl millet in West Africa, Pucher *et al.* (2015), reported plant height variation from 129 cm to 293 cm, panicle length from 17 cm to 89 cm and panicle circumference from 6 cm to 11 cm and a mean of 38.0 mg kg^{-1} for Fe and 34.9 mg kg^{-1} for Zn (Pucher *et al*, 2014). The wider plant height and panicle length ranges than the observation in this present study could be due to the larger number of genotypes (360) evaluated whereas the lower ranges for grain Fe and Zn content was due to the number of landraces (347). In India on the basis of the means of two environments, Govindaraj *et al.* (2013), reported variation from 30 to 80 mg kg^{-1} Fe and 20 to 70 mg kg^{-1} Zn which are considerably wider than the ranges observed in the present study. One explanation for this might be the higher parents that combining good used by Govindaraj *et al.* (2013).

Based on mean performance, and according to AMMI biplot, the different hybrids exhibited different pattern of adaptability very important for stabilization of crop production over regions and years. All the groups of genotypes that the distribution of points in the AMMI biplot revealed scattered close to the origin, showed minimal interaction with environments, then more stable. The remaining genotypes scattered away from the origin in the biplot were more sensitive to environmental interactive forces, then instable. Misra *et al.* (2009) and Lubadde *et al.* (2016) also reported stables as well as instable pearl millet genotypes using AMMI biplot.

More than 40% hybrids had mean that exceeded the grand mean and among them, 15.68%, 6.12% and 15.90% respectively for grain yield, grain Fe and Zn content had IPCA scores close to zero, indicated their general adaptability over the environment. Sumath *et al.* (2017) and Abuali *et al.* (2014) also identified some adaptability in hybrids of pearl millet and hybrids of maize respectively using the mean and IPCA values. The rest of 84.32%, 93.88% and 84.10% are conceived as specific adaptability to environment (Sumathi *et al*, 2017; Adjebeng-Danquah *et al*, 2017; Pucher *et al*, 2015), suggesting the need to identify and select location specific genotypes for different environments (Adjebeng-Danquah *et al,* 2017). Alternatively, stability analysis can be performed to identify genotypes whose performance remains stable over several years and environments (Adjebeng-Danquah *et al,* 2017; Abuali *et al,* 2014; Mutegi, 2009). Then, analysis of interaction of genotypes with locations and other agro-ecological conditions would be helpful for getting information on adaptability and stability of performance of genotypes (Abuali *et al,* 2014; Yan *et al,* 2007).

AMMI analysis (Becker HC and Leon J, 1988; Zobel *et al,* 1988; Purchase, 2000; Farshadfar *et al,* 2011) gives estimate of total G×E interaction effect of each genotype and also further partitions it into interaction effects due to individual environments. Low G × E interaction of a genotype indicates stability of the genotype over the range of environments. A genotype showing high positive interaction in an environment obviously has the ability to exploit the agro-ecological or agro-management conditions of the specific environment and is therefore best suited to that environment. AMMI analysis permits estimation of interaction effect of a genotype in each environment and it helps to identify genotypes best suited for specific environmental conditions. Though analysis of G×E interaction of multilocation yield data in AMMI model have been reported by Sumathi *et al.* (2017) Misra *et al.* (2009) and Hariprasanna *et al.* (2008) whereas Bachir *et al.* (2014), Pucher et al. (2015) reported stability for grain Fe and Zn content in pearl millet. All these workers found significant G×E interaction for grain yield as well as for grain Fe and Zn content and stressed the usefulness of AMMI analysis for selection of promising genotypes for specific locations or environmental conditions.

Additive main effect and multiplicative interaction (AMMI), stability value (ASV) has been successfully used in several studies to rank the genotypes based on the least score (Adjebeng-Danquah *et al,* 2017; Mallikarjuna *et al,* 2015; Pucher *et al,* 2015; Bachir *et al,* 2014; Yan *et al,* 2007). Low scores represent the most stable genotypes whilst those with high values are less stable genotypes. Sumathi *et al.* (2017) also reported stability in hybrids of pearl millet using ASV values. Stability alone for grain yield, grain Fe and Zn content performance may not always be adequate since a consistently low yielding genotype can still be stable (Abuali *et al,* 2014; Kang MS and Pham HM, 1991). Therefore, the stability index (SI) similar to genotype stability index (GSI) proposed by Fardshadfar. (2008) integrates both yield and stability across environments into a single index, to select varieties. Hybrids with lower SI for grain yield, grain Fe and Zn are considered as high yielding, high grain Fe and Zn density and stable. Therefore, their hybrids are desirable since they combine high mean performance of their traits with stability (Tumuhimbise *et al,* 2014; Farshadfar *et al,* 2011). Few hybrids from the tested hybrids combined their three-desirable character, indicated the need for testing more hybrids in more environments. However, the hybrids with high yielding, high grain Fe and Zn, high ASV scores resulting in high SI scores can be recommended for specific environments where they performed well (Adjebeng-Danquah *et al*, 2017).

Number of days to 50 per cent flowering, had positive and significant association ($P<0.05$) with grain Fe and Zn would suggest that the earlier hybrids will have grain with more Fe and Zn content. Plant height was significantly and positively correlated to panicle length and grain yield while, panicle length and panicle circumference were positively associated to grain yield would suggest that the taller hybrids will have long and larger panicle that significantly contributes to its height grain yield. Similar observations were made by Sumathi *et al.* (2017) and Bachir *et al.* (2013). The negative correlations among grain yield and grain Fe and Zn can be improved though identification of high yield and high Fe and Zn QTL and pyramiding them in the parental lines using marker-assisted selection (Govindaraj *et al,* 2013; Yadav OP and Rai KN, 2013). Grain Fe was found to have highly significant positive correlation with Zn. Similar results were reported by Kanatti *et al.* (2014), Pucher *et al.* (2014), and Velu *et al.* (2011). This showed that the underlying physiological processes determining both micronutrients were largely associated and improvement of one trait can improve the other. This would imply that recurrent selection can be effectively used for intra population improvement of Fe and Zn densities (Govindaraj *et al,* 2013).

CONCLUSION AND OUTLOOK

Results of the combining ability assessment showed that genetic variability for days to 50% flowering, plant height, panicle length and panicle circumference to be predominantly under additive genetic control, implying that intra-population improvement for these traits is likely to be highly effective. Nevertheless, the genetic variability for grain yield, grain Fe and Zn was found to be predominantly under non additive genetic control thought low GCA/SCA ratio for grain yield, Fe and Zn at present decreases the predictability of hybrids by GCA values, thus a two-step selection procedure based on both GCA and SCA might be preferable, at least in the medium term. Highly significant and positive correlation between performance *per se* of parental line and their general combining ability (GCA) for almost all the traits showed that parental lines of potential hybrids with high GCA can be effectively selected based on their performance *per se*, thus enhancing the breeding efficiency. But the best hybrids combinations observed in cross involved poor as well as good combining parents, suggested that efficiency breeding can also be found though some compatible gene interactions. Lack of correlation of Fe and Zn densities with grain yield in inbred lines, but significant negative correlation in hybrids merits further investigation as these results have direct bearing on the efficiency of breeding high-yielding hybrids with high levels of Fe and Zn densities. Crosses identified as best hybrids merits further investigation in different agroclimatic zones to confirm their stable superior performance.

Identification and improvement of superior restorers from variability generated via hybridization are crucial for pearl millet hybrid breeding program. Thus, the restorer's improvement trial elucidated the inheritance of grain yield, its related traits and grain Fe and Zn content in pearl millet using a diallel mating design. ICMR 157002 was good general combiner for days to 50% flowering, plant height, panicle length, biomass yield, grain Fe and Zn content, and other parents with good combining ability, could be exploited as donor parents in improving the restorer gene pool.

The superior and promising crosses having high *per se* performance; GCA and significant positive SCA effects for most of the agronomic and morphological traits can be utilised. ICMX 1770192, ICMX 1770198, ICMX 1770200, ICMX 1770205, ICMX 1770209 and ICMX 177213 were early flowering and yielding high, therefore recommended that, these genotypes should be included in the restorer improvement program in that, the likelihood of obtaining transgressive segregants from segregating generations of these crosses is high and should therefore be exploited. The crosses ICMX 1770197, ICMX 17720204, ICMX 1770206 and ICMX 1770217 showed high grain Fe and Zn content. All the superior crosses identified in should be further tested on a wide range of environments for stability and adaptation. Reciprocal effects revealed the careful selection of parents as male or female depending on the trait of inheritance. The GCA effect is lower than the SCA effect lead to a low predictability ratio, indicated the dominance of non-additive gene action for these traits. Thus, the improvement can be achieved through simple selection methods or pedigree breeding. Selection criteria to improve the restorer lines should focus on plants with early maturity, medium plant height, long panicle, as these traits have high genetic correlation with grain yield and grain Fe and Zn content. QTL analysis should follow to identify the gene responsible of grain yield, grain Fe and Zn and improve the negative association between grain yield and grain Fe and Zn.

Results of the standard heterosis study highlights the potential to increase pearl millet productivity thought the development of single and top cross hybrids in West Africa. The superiority of the test hybrids over the check variety indicates the economic advantage of top cross hybrids over single cross hybrids for grain yield whereas in the other hand showed the biofortification advantage of single cross hybrids over top cross hybrids. This result might be an indication of, the more adaptation of top cross in the tested environments and the good combining of pure lines in single cross hybrids for producing biofortified hybrids. Thereby, for increase grain yield in West Africa, top cross hybrid performs well due to the already adaptation of parents in the region, while the single cross hybrid is better for biofortification. This indicated that advantage can be win by including grain Fe and Zn in the adapted OPVs identified as top cross hybrids parents by back cross breeding. Also, the heterotic groups should be identified to benefit more heterosis for grain yield as well as for grain Iron and Zinc content. Genotype × environment interaction was significant for most of the traits indicating the need for additional test with more hybrids in more environments before making effective selection. This study showed that it is very difficult to combine adaptability of high performed hybrid with stability unless the number of hybrids tested is greater. More than 40% of hybrids had significant higher grain yield, grain Fe and Zn than the overall mean. These genotypes can be evaluated in more season and environments to assess more their adaptability for possible recommendation for release to farmers for cultivation. The sum of the yield, grain Fe and Zn content and their stability rankings showed many hybrids with high mean values and more stability. Among these hybrids, it will be useful to use the first ten (10%) hybrids which have hight grain yield, grain Fe and Zn in multilocation trial including more variable environment to confirm the desirability.

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ANNEX

Annexe 1. Pedigree of parents and crosses for line x Tester trial

S no.	Designation	Crosses
Lines		
1	ICMB 177001	ICMB 177001
2	ICMB 177002	ICMB 177002
3	ICMB 177003	ICMB 177003
4	ICMB 177004	ICMB 177004
5	ICMB 177005	ICMB 177005
6	ICMB 177006	ICMB 177006
7	ICMB 177007	ICMB 177007
8	ICMB 177090	ICMB 177090
9	ICMB 177111	ICMB 177111
Testers		
1	Exbornu	Exbornu
2	ICMR 08666	ICMR 08666
3	ICMR 08777	ICMR 08777
4	ICMR 08888	ICMR 08888
5	ICMR 09666	ICMR 09666
6	ICMR 1301	ICMR 1301
7	ICMR 157003	ICMR 157003
8	ICMR 157004	ICMR 157004
9	ICMR 167011	ICMR 167011
10	ICMR IS 16006	ICMR IS 16006
11	ICMR IS 16007	ICMR IS 16007
12	ICMR IS 16008	ICMR IS 16008
Crosses		
1	ICMH 177016	ICMB 177001×Exbornu
2	ICMX 187876	ICMB 177001×ICMR 08666
3	ICMX 187877	ICMB 177001×ICMR 08777

Annexe 1. Pedigree of parents and crosses for line x Tester trial

S no.	Designation	Crosses
4	ICMX 187878	ICMB 177001×ICMR 08888
5	ICMX 187880	ICMB 177001×ICMR 09666
6	ICMX 187882	ICMB 177001×ICMR 1301
7	ICMH IS 16008	ICMB 177001×ICMR 157003
8	ICMH IS 16009	ICMB 177001×ICMR 157004
9	ICMX 187989	ICMB 177001×ICMR 167011
10	ICMX 187990	ICMB 177001×ICMR IS 16006
11	ICMX 187991	ICMB 177001×ICMR IS 16007
12	ICMX 187992	ICMB 177001×ICMR IS 16008
13	ICMH 177017	ICMB 177002×Exbornu
14	ICMX 187883	ICMB 177002×ICMR 08666
15	ICMX 187885	ICMB 177002×ICMR 08777
16	ICMH 177111	ICMB 177002×ICMR 08888
17	ICMH 177022	ICMB 177002×ICMR 09666
18	ICMX 187766	ICMB 177002×ICMR 1301
19	ICMH IS 16012	ICMB 177002XICMR 157003
20	ICMH IS 16013	ICMB 177002×ICMR 157004
21	ICMX 187995	ICMB 177002×ICMR 167011
22	ICMX 187996	ICMB 177002×ICMR IS 16006
23	ICMX 187997	ICMB 177002×ICMR IS 16007
24	ICMX 187998	ICMB 177002×ICMR IS 16008
25	ICMH 177020	ICMB 177003×Exbornu
26	ICMX 187891	ICMB 177003×ICMR 08666
27	ICMX 187892	ICMB 177003×ICMR 08777
28	ICMX 187893	ICMB 177003×ICMR 08888
29	ICMX 187895	ICMB 177003×ICMR 09666
30	ICMX 187897	ICMB 177003×ICMR 1301
31	ICMX 1871001	ICMB 177003×ICMR 157003

Annexe 1. Pedigree of parents and crosses for line x Tester trial

S no.	Designation	Crosses
32	ICMX 1871002	ICMB 177003×ICMR 157004
33	ICMX 1871003	ICMB 177003×ICMR 167011
34	ICMX 1871004	ICMB 177003×ICMR IS 16006
35	ICMX 1871005	ICMB 177003×ICMR IS 16007
36	ICMX 1871006	ICMB 177003×ICMR IS 16008
37	ICMH 177023	ICMB 177004×Exbornu
38	ICMX 187854	ICMB 177004×ICMR 08666
39	ICMX 187856	ICMB 177004×ICMR 08777
40	ICMX 187857	ICMB 177004×ICMR 08888
41	ICMX 187859	ICMB 177004×ICMR 09666
42	ICMX 187861	ICMB 177004×ICMR 1301
43	ICMX 1871013	ICMB 177004×ICMR 157003
44	ICMX 1871014	ICMB 177004×ICMR 157004
45	ICMH 177002	ICMB 177004×ICMR 167011
46	ICMX 1871008	ICMB 177004×ICMR IS 16006
47	ICMX 1871009	ICMB 177004×ICMR IS 16007
48	ICMX 1871010	ICMB 177004×ICMR IS 16008
49	ICMX 1871038	ICMB 177005×Exbornu
50	ICMX 187862	ICMB 177005×ICMR 08666
51	ICMX 187864	ICMB 177005×ICMR 08777
52	ICMX 187865	ICMB 177005×ICMR 08888
53	ICMX 187867	ICMB 177005×ICMR 09666
54	ICMX 187868	ICMB 177005×ICMR 1301
55	ICMH 147008	ICMB 177005×ICMR 157003
56	ICMX 1871017	ICMB 177005×ICMR 157004
57	ICMX 1871018	ICMB 177005×ICMR 167011
58	ICMX 1871019	ICMB 177005×ICMR IS 16006
59	ICMX 1871020	ICMB 177005×ICMR IS 16007

Annexe 1. Pedigree of parents and crosses for line x Tester trial

S no.	Designation	Crosses
60	ICMX 1871021	ICMB 177005×ICMR IS 16008
61	ICMH 177018	ICMB 177006×Exbornu
62	ICMX 187870	ICMB 177006×ICMR 08666
63	ICMX 187872	ICMB 177006×ICMR 08777
64	ICMX 1871046	ICMB 177006×ICMR 08888
65	ICMX 187875	ICMB 177006×ICMR 09666
66	ICMX 187769	ICMB 177006×ICMR 1301
67	ICMH 147010	ICMB 177006×ICMR 157003
68	ICMH 147009	ICMB 177006×ICMR 157004
69	ICMX 1871023	ICMB 177006×ICMR 167011
70	ICMX 1871024	ICMB 177006×ICMR IS 16006
71	ICMX 1871025	ICMB 177006×ICMR IS 16007
72	ICMX 1871029	ICMB 177006×ICMR IS 16008
73	ICMH 177019	ICMB 177007×Exbornu
74	ICMX 187068	ICMB 177007×ICMR 08666
75	ICMX 187762	ICMB 177007×ICMR 08777
76	ICMX 1871027	ICMB 177007×ICMR 08888
77	ICMX 187763	ICMB 177007×ICMR 09666
78	ICMX 187765	ICMB 177007×ICMR 1301
79	ICMX 1871029	ICMB 177007×ICMR 157003
80	ICMX 1871030	ICMB 177007×ICMR 157004
81	ICMX 1871032	ICMB 177007×ICMR 167011
82	ICMX 1871033	ICMB 177007×ICMR IS 16006
83	ICMX 1871034	ICMB 177007×ICMR IS 16007
84	ICMX 1871035	ICMB 177007×ICMR IS 16008
85	ICMX 187825	ICMB 177090×Exbornu
86	ICMX 187803	ICMB 177090×ICMR 08666
87	ICMX 187806	ICMB 177090×ICMR 08777

Annexe 1. Pedigree of parents and crosses for line x Tester trial

S no.	Designation	Crosses
88	ICMX 187807	ICMB 177090×ICMR 08888
89	ICMX 187808	ICMB 177090×ICMR 09666
90	ICMX 187786	ICMB 177090×ICMR 1301
91	ICMX 187812	ICMB 177090×ICMR 157003
92	ICMX 187813	ICMB 177090×ICMR 157004
93	ICMX 187826	ICMB 177090×ICMR 167011
94	ICMX 187822	ICMB 177090×ICMR IS 16006
95	ICMX 187823	ICMB 177090×ICMR IS 16007
96	ICMX 187824	ICMB 177090×ICMR IS 16008
97	ICMX 187848	ICMB 177111×Exbornu
98	ICMX 187827	ICMB 177111×ICMR 08666
99	ICMX 187829	ICMB 177111×ICMR 08777
100	ICMX 187830	ICMB 177111×ICMR 08888
101	ICMX 187832	ICMB 177111×ICMR 09666
102	ICMX 187788	ICMB 177111×ICMR 1301
103	ICMX 187836	ICMB 177111×ICMR 157003
104	ICMX 187790	ICMB 177111×ICMR 157004
105	ICMX 187853	ICMB 177111×ICMR 167011
106	ICMX 187849	ICMB 177111×ICMR IS 16006
107	ICMX 187850	ICMB 177111×ICMR IS 16007
108	ICMX 187851	ICMB 177111×ICMR IS 16008

Annexe 2. Association of agronomic and morphological traits in Line x Testers of pearl millet (*Pennisetum glaucum* L.) at Sadore and Gampela.

Traits	**Days to 50% flowering**	**Plant height**	**Panicle length**	**Panicle circumference**	**Grain yield**	**Grain Fe content**	**Grain Zn content**
Days to 50% flowering	1.00						
Plant height	-0.35**	1.00					
Panicle length	-0.16*	0.20**	1.00				
Panicle circumference	-0.16*	0.46**	-0.14	1.00			
Grain yield	-0.23**	0.66**	0.17*	0.40**	1.00		
Grain Fe content	-0.07	-0.04	-0.12	0.19*	-0.19*	1.00	
Grain Zn content	-0.01	-0.06	-0.09	0.10	-0.18*	0.76**	1.00

*,** r value significant at P 0.05 and 0.01, respectively.

Annexe 3. Pedigree information of the parents utilised and crosses generated in R × R diallel of pearl millet (Pennisetum glaucum L.), ICRISAT, Sadore, Niger.

Genotype	Pedigree
Parents	
ICMR 157001	PE00397_B_B_1_1_B
ICMR 157002	PE00349_B_2_1_B
ICMR 157003	PE11291_B_2_1_B
ICMR 157004	PE11322_B_B_3_1_B
ICMR 157005	PE11322_B_B_4_1_B
ICMR 167011	3/4exborno_P30_1_1_1_B
Direct crosses	
ICMX 1770190	ICMR 157001 × ICMR 157002
ICMX 1770191	ICMR 157001 × ICMR 157003
ICMX 1770192	ICMR 157001 × ICMR 157004
ICMX 1770193	ICMR 157001 × ICMR 157005
ICMX 1770194	ICMR 157001 × ICMR 167011
ICMX 1770196	ICMR 157002 × ICMR 157003
ICMX 1770197	ICMR 157002 × ICMR 157004
ICMX 1770198	ICMR 157002 × ICMR 157005
ICMX 1770199	ICMR 157002 × ICMR 167011
ICMX 1770202	ICMR 157003 × ICMR 157004
ICMX 1770203	ICMR 157003 × ICMR 157005
ICMX 1770204	ICMR 157003 × ICMR 167011
ICMX 1770208	ICMR 157004 × ICMR 157005
ICMX 1770209	ICMR 157004 × ICMR 167011
ICMX 1770214	ICMR 157005 × ICMR 167011
Reciprocal crosses	
ICMX 1770195	ICMR 157002 × ICMR 157001
ICMX 1770200	ICMR 157003 × ICMR 157001
ICMX 1770205	ICMR 157004 × ICMR 157001

Annexe 3. Pedigree information of the parents utilised and crosses generated in R × R diallel of pearl millet (Pennisetum glaucum L.), ICRISAT, Sadore, Niger.

Genotype	Pedigree
ICMX 1770210	ICMR 157005 × ICMR 157001
ICMX 1770215	ICMR 167011 × ICMR 157001
ICMX 1770201	ICMR 157003 × ICMR 157002
ICMX 1770206	ICMR 157004 × ICMR 157002
ICMX 1770211	ICMR 157005 × ICMR 157002
ICMX 1770216	ICMR 167011 × ICMR 157002
ICMX 1770207	ICMR 157004 × ICMR 157003
ICMX 1770212	ICMR 157005 × ICMR 157003
ICMX 1770217	ICMR 167011 × ICMR 157003
ICMX 1770213	ICMR 157005 × ICMR 157004
ICMX 1770218	ICMR 167011 × ICMR 157004
ICMX 1770219	ICMR 167011 × ICMR 157005

Annexe 4. Pedigree information of single and top cross hybrids

Single cross hybrids

ICMH 1201	ICMA1201 × ICMR1201
ICMH 1301	ICMA 1301 × ICMR 1301
ICMH 157222	ICMA 177006 × ICMR 167011
ICMH 177002	ICMA 177004 × ICMR 167011
ICMH 177022	ICMA 177002 × ICMR 09666
ICMH 177111	ICMA 177002 × ICMR 08888
ICMX 1871003	ICMA 177003 × ICMR 167011
ICMX 1871018	ICMA 177005 × ICMR 167011
ICMX 1871023	ICMA 177006 × ICMR 167011
ICMX 1871027	ICMA 177007 × ICMR 08888
ICMX 1871032	ICMA 177007 × ICMR 167011
ICMX 1871037	ICMA 177029 × ICMR 1301
ICMX 1871048	ICMA 177021 × ICMR 1301
ICMX 1871049	ICMA 177022 × ICMR 1301
ICMX 1871050	ICMA 08888 × ICMR 1301
ICMX 187760	ICMA 177007 × ICMR 08888
ICMX 187762	ICMA 177007 × ICMR 08777
ICMX 187763	ICMA 177007 × ICMR 09666
ICMX 187765	ICMA 177007 × ICMR 1301
ICMX 187766	ICMA 177002 × ICMR 1301
ICMX 187769	ICMA 177006 × ICMR 1301
ICMX 187772	ICMA 177011 × ICMR 1301
ICMX 187773	ICMA 177012 × ICMR 1301
ICMX 187775	ICMA 177013 × ICMR 1301
ICMX 187778	ICMA 177015 × ICMR 1301
ICMX 187781	ICMA 177020 × ICMR 1301
ICMX 187786	ICMA 177090 × ICMR 1301
ICMX 187788	ICMA 177111 × ICMR 1301

Annexe 4. Pedigree information of single and top cross hybrids

ICMX 187803	ICMA 177090 × ICMR 08666
ICMX 187806	ICMA 177090 × ICMR 08777
ICMX 187807	ICMA 177029 × ICMR 08888
ICMX 187808	ICMA 177090 × ICMR 09666
ICMX 187826	ICMA 177090 × ICMR 167011
ICMX 187827	ICMA 177111 × ICMR 08666
ICMX 187829	ICMA 177111 × ICMR 08777
ICMX 187830	ICMA 177111 × ICMR 08888
ICMX 187832	ICMA 177111 × ICMR 09666
ICMX 187853	ICMA 177111 × ICMR 167011
ICMX 187854	ICMA 177004 × ICMR 08666
ICMX 187856	ICMA 177004 × ICMR 08777
ICMX 187857	LCICMA1 × ICMR 08888
ICMX 187859	ICMA 177004 × ICMR 09666
ICMX 187860	ICMA 177004 × ICMR 09999
ICMX 187861	ICMA 177004 × ICMR 1301
ICMX 187862	ICMA 177005 × ICMR 08666
ICMX 187864	ICMA 177005 × ICMR 08777
ICMX 187865	ICMA 177005 × ICMR 08888
ICMX 187867	ICMA 177005 × ICMR 09666
ICMX 187868	ICMA 177005 × ICMR 1301
ICMX 187870	ICMA 177006 × ICMR 08666
ICMX 187872	ICMA 177006 × ICMR 08777
ICMX 187875	ICMA 177006 × ICMR 09666
ICMX 187876	ICMA 177001 × ICMR 08666
ICMX 187877	ICMA 177001 × ICMR 08777
ICMX 187878	ICMA 177001 × ICMR 08888
ICMX 187880	ICMA 177001 × ICMR 09666
ICMX 187881	ICMA 177001 × ICMR 09999
ICMX 187882	ICMA 177001 × ICMR 1301

Annexe 4. Pedigree information of single and top cross hybrids

ICMX 187883	ICMA 177002 × ICMR 08666
ICMX 187885	ICMA 177002 × ICMR 08777
ICMX 187889	ICMA 177002 × ICMR 09999
ICMX 187891	ICMA 177003 × ICMR 08666
ICMX 187892	ICMA 177003 × ICMR 08777
ICMX 187893	ICMA 177003 × ICMR 08888
ICMX 187895	ICMA 177003 × ICMR 09666
ICMX 187897	ICMA 177003 × ICMR 1301
ICMX 187989	ICMA 177001 × ICMR 167011
ICMX 187995	ICMA 177002 × ICMR 167011

Top cross hybrids

ICMH 177016	ICMA 177001 × Exbornu
ICMH 177017	ICMA 177002 × Exbornu
ICMH 177018	ICMA 177006 × Exbornu
ICMH 177019	ICMA 177007 × Exbornu
ICMH 177020	ICMA 177003 × Exbornu
ICMH 177023	LCICMA1 × Exbornu
ICMH IS 16027	ICMA 177001 × ICMV IS 92222
ICMH IS 16037	ICMA 177001 × ICMV IS 94206
ICMH IS 16038	ICMA 177001 × ZANGO BADAU
ICMH IS 16040	ICMA 177001 × GAMOJI
ICMH IS 16044	ICMA 177001 × ICMV 167004
ICMH IS 16052	ICMA 177001 × ICMV IS 99001
ICMH IS 16075	ICMA 177002 × GAMOJI
ICMH IS 16076	ICMA 177002 × ZANGO BADAU
ICMH IS 16120	ICMA 177003 × ICMV 167002
ICMH IS 16187	ICMA 177006 × ICMV IS 99001
ICMH IS 16214	ICMA 177006 × ICMV IS 89305
ICMX 187001	ICMA 177002 × GB 8735
ICMX 187011	ICMA 177002 × Ankoutess

Annexe 4. Pedigree information of single and top cross hybrids

ICMX 187018	ICMA 177002 × Jirani
ICMX 187020	ICMA 177002 × ICMV IS 90309
ICMX 187023	ICMA 177001 × Exbornu
ICMX 187026	ICMA 177001 × Chakti
ICMX 187031	ICMA 177001 × Ankoutess
ICMX 187040	ICMA 177001 × ICMV IS 90309
ICMX 187041	ICMA 177004 × GB 8735
ICMX 187042	ICMA 177004 × ICMV IS 99001
ICMX 187046	ICMA 177004 × Chakti
ICMX 187048	ICMA 177004 × ICMV 167002
ICMX 187050	ICMA 177004 × ICMV IS 94206
ICMX 187054	ICMA 177004 × ICMV 167005
ICMX 187068	ICMA 177007 × ICMV 167002
ICMX 1871038	ICMA 177005 × Exbornu
ICMX 1871039	ICMA 177090 × ICMV IS 99001
ICMX 1871040	ICMA 177090 × ICMV IS 94206
ICMX 1871041	ICMA 177090 × ICMV IS 92222
ICMX 1871042	ICMA 177111 × ICMV IS 94206
ICMX 1871043	ICMA 177111 × ICMV IS 92222
ICMX 1871044	ICMA 177111 × ZONGO
ICMX 1871045	ICMA 04999 × Chakti
ICMX 187572	ICMA 177001 × ZATIB
ICMX 187848	ICMA 177111 × Exbornu
Chakti (C1)	ICTP 8203-Fe-2
ICMV 167005 (C2)	PE05578

C1, check 1; C2, Check 2

PUBLICATIONS

Zakari H, Riyazaddin M, Prakash IG, Govindaraj M, Moussa T. Improvement of Restorer Lines for Strengthening Pearl Millet (*Pennisetum glaucum* L.) Hybrid Breeding in West and Central Africa. Journal of Agricultural and Crop Research. 2019; 7(11): 204-214.