Journal of Agricultural Science; Vol. 16, No. 11; 2024
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

On-Farm Grain Yield Stability and Farmer Perceptions on Pre-release Pearl Millet Lines in Zimbabwe

Ruvarashe Loveness Mhuruyengwe[1], Tshifhiwa Paris Mamphogoro[2], Olivia Mukondwa[3] & Casper Nyaradzai Kamutando[1]

[1] Department of Plant Production Sciences and Technologies, University of Zimbabwe, Mount Pleasant Harare, Zimbabwe

[2] Gastro-Intestinal Microbiology and Biotechnology Unit, Agricultural Research Council-Animal Production, Irene, Pretoria, South Africa

[3] Crop Breeding Institute, Crops Research Division, Department of Research and Specialist Services, Harare Agricultural Research Centre, Fifth Street Extension, Causeway, Harare, Zimbabwe

Correspondence: Casper Nyaradzai Kamutando, Department of Plant Production Sciences and Technologies, University of Zimbabwe, P.O. Box MP 167, Mount Pleasant Harare, Zimbabwe. Tel: 263-713-232-033. E-mail: kamutandocn@gmail.com

Received: July 1, 2024 Accepted: September 2, 2024 Online Published: October 15, 2024

doi:10.5539/jas.v16n11p75 URL: https://doi.org/10.5539/jas.v16n11p75

Abstract

Farmer participation in on-farm research does not only accelerate information gathering but also results in adoption of new research products. Here, we report on-farm trials conducted across five districts of Matabeleland province in Zimbabwe to explicate grain yield stability and farmer perceptions on eight pre-release pearl millet (*Pennisetum glaucum* L.) lines. The results indicated that genotypic effects on grain yield were significant in both individual and across-site analysis of variance and that farmers prioritize earliness and grain yield as must-have traits in millet varieties. The five districts were grouped into two distinct environments, with four districts (*i.e.*, Bulilima, Gwanda, Matopos and Tsholotsho) in one group (*i.e.*, DGrp1) and Mangwe district forming the second group (DGrp2). Pearl millet pre-release lines PM1 (1.425 kg ha^{-1}), PM9 (1.043 kg ha^{-1}) and PM6 (761.8 kg ha^{-1}) showed high yield, stability and were the most preferred by farmers. In conclusion, on-farm trials may offer the quickest possible solution to boost low-pearl millet production resulting from the continuous use of unproductive landraces and old varieties by farmers.

Keywords: on-farm trials, pearl millet, farmer preference, stability, grain yield

1. Introduction

Pearl millet (*Pennisetum glaucum* L.) is a drought-resilient crop known to originate in Africa (Oumar et al., 2008). It is an important cereal in arid and semi-arid regions of the world and ranks sixth in terms of contribution to global cereal supply after wheat, rice, maize, barley, and sorghum (Jukanti et al., 2016). In Zimbabwe, pearl millet production is mainly concentrated in the southern parts of the country, which are classified as arid and semi-arid, as they receive low rainfall that is erratic and unevenly distributed. Millet production in these areas is possible, given the drought-resilient characteristics of the crop that enable it to withstand extreme environmental conditions. Despite its potential as a key food security crop, pearl millet production is affected by both biotic and abiotic factors. Among the biotic constraints, most yield losses are attributed to predators particularly birds (Raheem et al., 2021), fungal diseases such as Downey mildew (Sharathchandra et al., 2004), striga infestation (Drabo et al., 2019), and bacterial diseases (Khorwal, Sharma, & Agrawal, 2023). Most cereal crops including pearl millet, face the serious challenge of depredation by quelea birds (*i.e.*, the red-billed types), and most farmers are reluctant to grow pearl millet because of the fear of large flocks of these destructive birds that can potentially wipe out the whole crop (Phiri et al., 2019). On the other hand, climate change induced abiotic stresses have also been reported as important determinants of yield loses in pearl millet. For example, severe heat and drought stress have been reported to cause significant yield losses (Vadez et al., 2012). Additionally, low soil fertility, especially in soils deficient in nitrogen and phosphorus, is rendered unsuitable for pearl millet production, although the crop can withstand these stress factors better than other cereals (Moharana et al., 2012). Several strategies can be employed to minimize the impact of abiotic and biotic stresses on pearl millet productivity. Synthetic pesticides are commonly used to control pests (Gahukar & Reddy, 2019) and diseases (Khorwal, Sharma, & Agrawal, 2023). However, most pesticides affect ecosystem functions and biodiversity (Schäfer, 2012). Given the shortcomings of these strategies, plant breeding (*i.e.*, genetic crop improvement) remains a sustainable strategy to promote crop productivity under ever-changing climate and socioeconomic scenarios (Sharma et al., 2021). The Crop Breeding Institute (CBI), a research arm within the Ministry of Lands, Agriculture, Water, Fisheries & Rural Development in Zimbabwe, initiated a pearl millet breeding program with the objective of developing varieties productive under the diverse agro-ecologies in sub-Saharan Africa (SSA). Over the years, several improved varieties (*i.e.*, resistant/tolerant to some common biotic and abiotic stresses) have been released, including Okashana 1, Pmv1, Pmv2, Pmv3, Pmv4, and Pmv5. Generally, most of the local landraces are very tall and late maturing; these were crossed with lines obtained from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to produce higher yielding, early maturing superior varieties. Although improved genotypes continue to be released on a yearly basis, the rate of adoption of these genotypes by farmers remains very low (Alumira & Rusike, 2005). Lack of sufficient knowledge concerning agronomic practices and the economic importance of the newly developed genotypes by farmers is one of the factors resulting in low adoption rates (Omanya et al., 2007). Farmers who are the end users of the products are normally left out in the variety selection process, resulting in reduced adoption of new varieties. The involvement of farmers in variety selection can go a long way in speeding up the rate of adoption of new varieties, and early studies supported that the involvement of farmers in variety selection (*i.e.*, participatory variety selection; PVS) is the quickest and most effective way to promote the adoption of new varieties by farmers. Concisely, the amalgamation of efforts by plant breeders and farmers will boost pearl millet production in Zimbabwe through the increased adoption of improved varieties. Therefore, the aim of this study was to elucidate on-farm grain yield stability and farmer perceptions of pre-release pearl millet lines in Zimbabwe.

2. Materials and Methods

2.1 Germplasm and Test Locations

The on-farm trials consisted of eight experimental pearl millet pre-release lines developed by CBI, which were evaluated together with two check varieties (one commercial variety developed by ICRISAT and a farmer's own variety) (Table 1). These were evaluated in farmers' fields during the 2019-20 season across five districts in the Matabeleland province (Table 2). These districts represent areas where pearl millet is predominantly grown in Zimbabwe and are characterized by low rainfall that is poorly and unevenly distributed, mid-season droughts, and high temperatures (Mugandami et al., 2012).

Table 1. Description of the eight pre-release pearl millet lines evaluated alongside two checks, in on-farm trials conducted at five sites during the 2019-20 summer season in Zimbabwe

Code	**Genotype**	**Type and breeding status**	**Origin**	**Treatment type**
PM1	SDMV 95023	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM2	SDMV 90031	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM3	SMDV 96061	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM4	OKASHANA-1	Grain/Released/ICRISAT	Zimbabwe	Check
PM5	SDMV 93032	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM6	TSHOLOTSHO-B	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM7	SDMV 94018	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM8	SDGP 2052	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM9	SDGP 95009	Grain/Advanced/CBI	Zimbabwe	Experimental line
PM10	Farmer variety	Farmer Check Variety	Zimbabwe	Check

Table 2. Description of the trial sites used to evaluate the eight pre-release pearl millet lines and local checks during the 2019-20 summer season in Zimbabwe

Site code	Testing site	Natural region	Average rainfall (mm)	Soil type
E_1	Bulilima	IV	400-500	Sandy loam
E_2	Gwanda	IV	< 700	Loamy
E_3	Mangwe	IV	450- 650	Sandy loam
E_4	Matopos	IV	450-600	Red clay
E_5	Tsholotsho	IV	400-500	Sandy loam

2.2 Trial Establishment and Agronomic Data Collection

The 10 pearl millet genotypes were established using a Randomized Complete Block Design (RCBD), with two replications. The farmers managed the on-farm trials, and each farmer acted as a replicate. Each genotype was planted in a plot of 5 rows, 5m long with an in-row and inter-row spacing of 0.2 m and 0.75 m, respectively, resulting in a plant population of 125 plants per gross plot. During harvesting, only three rows at the center were considered with a 0.5 m border on each end of the rows discarded to eliminate border effects. This left a net plot size of 9 m^2 (*i.e.*, 3 rows × 0.75 m × 4 m row length). Agronomic field data on plant height (PHT; obtained by measuring the distance between the base and the tip of the main head (panicle) measured at physiological maturity), days to physiological maturity (DPM; duration from planting until a black layer is formed above the hilar region of the seed), exertion (EXTN; distance from the flag leaf to the base of the head), and productive tillers (PDT; obtained by counting the number of tillers from five tagged plants within the plot and dividing the total by five to obtain the average number of tillers per plant) were measured.

2.3 Participatory Variety Selection Procedure

Participatory variety selection (PVS) was performed to determine the most important trait for selection and to identify the genotypes most preferred by farmers. A set of procedures were employed to determine the most important traits and identify the most preferred genotypes.

2.3.1 Determination of Farmers' Most Important Traits and Their Ranking in Variety Selection

Focus Group discussions were conducted across the five districts to identify the traits most preferred by the farmers. The pairwise ranking matrix method was used to conduct focus group discussions, where an individual item was compared to the rest of the items such that the summation of the number of times it was chosen was obtained. The item with the largest number of items was considered the most important; hence, it was the most preferred. From the pairwise ranking matrix performed during the focus group discussions, the most important traits for farmers were earliness, grain yield, drought tolerance, and tillering. Thereafter, the researcher allocated weights of 40%, 30%, 20% and 10% to these traits respective of their importance as per farmer selection.

2.3.2 Selection of Most Preferred Genotypes

Two farmers (one male and one female) per trial site participated in establishing the on-farm trials, and this was done across all sites (*i.e.*, districts). Local farmers were then invited to participate in variety selection at physiological maturity to choose their preferred genotypes. Among the invited local farmers, 10 of them took part in scoring the 10 genotypes for four traits (*i.e.*, earliness, grain yield, drought tolerance and tillering) on a scale of 1 (*i.e.*, denoting a poor genotype) to 5 (*i.e.*, denoting a very good genotype). To avoid bias, the farmers scored each plot, and the plots were assigned numbers without labelling the genotype names. The final ranking of each genotype across sites was determined using the overall weighted score performance. The overall weighted score was obtained by summing the products of the trait scores and their respective weighted percentages. The overall genotype score performance *i.e.*, a predictive measure of variety performance was considered helping in variety selection, reducing reliability on phenotypic observations, also enhancing improved decision by farmers in selecting varieties that are more likely to perform well under specific environmental conditions and management practices. The weighted scores of the farmers most important traits that was allocated weights by the researcher was considered in calculating the overall genotype score performance which was calculated as follows:

$$\text{Overall Genotype Score Performance} = N\,[GY\,(g)\,(0.4) + DPM\,(d)\,(0.3) + DT\,(dt)\,(0.2) + T(t)\,(0.1)] \quad (1)$$

where, N = Total number of farmers who participated in PVS; GYD (g) = Grain yield score on a 1-5 scale; DMT (d) = Days to maturity score on a 1-5 scale; Drought tolerance (dt) = Drought tolerance score on a 1-5 scale; and Tillering (t) = Tillering score on a 1-5 scale.

2.4 Statistical Analysis

Individual and combined site analysis of variance (ANOVA) for all traits were performed using Genstat software version 17. Tukey's test was used to determine the differences between the treatment means at a 5% level of significance. Heritability estimates, genotypic and environmental variances were predicted using the Multi Environment Trial Analysis with R (META-R) software v2.1. Genotype + Genotype x Environment interaction (GGE) biplots were plotted using Genstat Software 17th Edition (Payne, 2009). The 'ranking' GGE biplot was used to identify stable genotypes, while the 'scatter' GGE biplot was used to depict genotypes adapted to specific environments (Yan et al., 2000). To determine the relationship between grain yield performance and overall genotype score performance (*i.e.*, farmers' preferences), a simple linear regression analysis was performed. Regression statistics were generated using the 'lm' function in the agricolae v1.3-1 R package and the linear relationships were visualized using the 'ggplot' function in the ggplot2 v3.3.5 R.

3. Results

3.1 On-Farm Grain-Yield Performance

The genotypic effects on grain yield were significant at all five testing sites ($p < 0.05$; Table 3). Across sites, genotypic and genotype × environment interaction (GEI) effects on grain yield were highly significant ($p < 0.001$; Table 4). The broad sense heritability (H^2) for grain yield was very high (70%) at both individual sites and across sites. The genotypic variance was more important than the environmental variance at all sites. Likewise, the genotypic variance component for grain yield was higher than the GEI and error variance components across sites. On individual site analysis, the Mangwe district showed the highest mean grain yield of 754 kg ha^{-1} whilst Matopos had the lowest mean grain yield (626 kg ha^{-1}). Across sites, the mean grain yield of the pearl millet lines ranked from 273 kg ha^{-1} to 1425 kg ha^{-1} with PM1 (1425 kg ha^{-1}) being the best performing genotype and PM2 (273 kg ha^{-1}), the least performing genotype (Table 5). The best performing genotype, *i.e.*, PM1 performed better than the check varieties PM 10 (732.6 kg ha^{-1}) and PM4 (local check; 808.8 kg ha^{-1}) however, the difference in yield was not significant (LSD = 356.89 kg ha^{-1}; Table 5).

Table 3. Individual site ANOVA for grain yield data collected on on-farm PVS trials of pearl millet pre-release varieties established across five districts in the arid and semi-arid regions of Zimbabwe, during the 2019-20 summer season

Environment	Grand mean	MS	CV (%)	LSD	Heritability	EV	GV
Bulilima	632	234254**	17.88	398.70	0.87	31069.29	101592.7
Gwanda	720	375079**	12.73	476.13	0.84	63656	158033.2
Mangwe	753	326310**	0.90	489.60	0.75	46841	142052
Matopos	626	340178***	18.71	229.69	0.96	13734.22	163250.5
Tsholotsho	650	393090***	21.09	268.89	0.95	18820.79	187134.8

Note. **, ***: Significant at 0.01 and 0.001 probability level.

Table 4. Across site ANOVA for grain yield and other agronomic traits on on-farm PVS trials of pearl millet pre-release varieties established across five districts in the arid and semi-arid regions of Zimbabwe ,during the 2019-20 summer season

Source of variation	Degrees of freedom	SS	MS
Districts	4	260405	65101
Farmers	1	3469	3469
Genotype	9	11670442	1296716***
Genotype x District	36	3349760	93049***
Residual	49	11670442	33759
Phenotypic variance			153799.71
Genotypic variance			120646.2
Environmental variance			33153.51
PCV (%)			57.97
GCV (%)			51.34
Broad sense heritability (%)			93.04
Least significance difference			356.89
Grand mean			676.56
Maximum			172
Minimum			1534
SEm (±)			41.36

Note. **, ***: Significant at 0.01 and 0.001 probability level.

Table 5. PVS genotype ranking across site as compared to researcher ranking

Code	**Genotype**	**Mean Grain Yield** (kg ha^{-1})	**Researcher ranking**	**Overall Genotype Score performance**	**Farmers ranking**
PM1	SDMV 95023	1425	1	146.9	1
PM2	SDMV 90031	273	10	117.8	7
PM3	SDMV 96061	325	9	130.2	4
PM4	OKASHANA-1	808.8	3	123.2	5
PM5	SMDV 93032	489.4	7	123.2	5
PM6	TSHOLOTSHO-B	761.8	4	134.5	3
PM7	SMDV 94018	344.6	8	114.7	8
PM8	SDGP 2052	562.4	6	107.3	9
PM9	SDGP 95009	1042.8	2	139.4	2
PM10	Farmer variety	732.6	5	103.3	10

3.2 On-Farm Grain Yield Stability and Specific Adaptation

Genotypes PM1, PM6 and PM9 were the best performers in terms of grain yield and showed to be highly stable as denoted by a short dotted green line from the AEC line as shown in Figure 1. Although it was highly stable, genotype PM2 had the lowest mean grain yield. The five sites clustered into two distinct groupings with the first grouping (*i.e.*, DGrp1) comprising Bulilima, Gwanda, Matopos, and Tsholotsho, while the Mangwe district formed the second grouping (DGrp2). PM1 was identified as the most ideal genotype under DGrp1, and PM10 under DGrp2 (Figure 2).

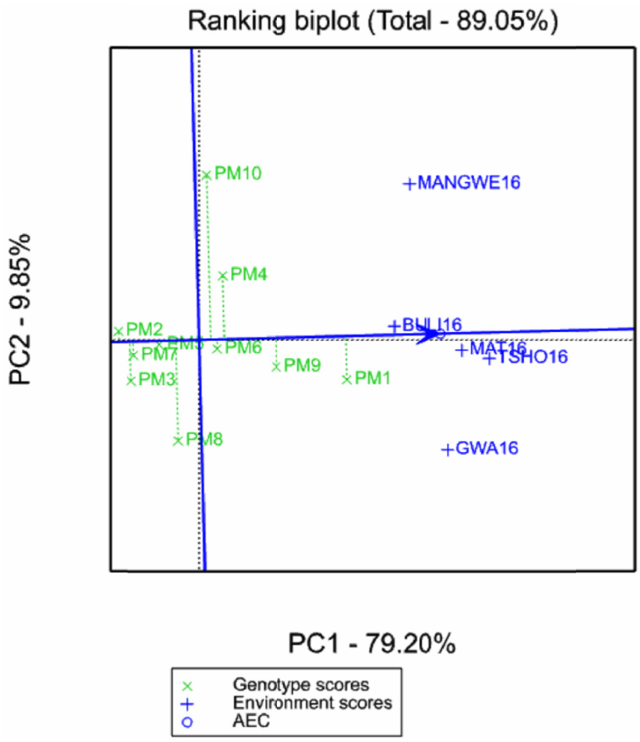

Figure 1. Ranking GGE biplot showing pre-release pearl millet stable to specific districts, classified within the arid and semi-arid regions in Zimbabwe. The lesser the distance of a genotype from the AEC line the more the stable and the larger the distance the lesser the stability

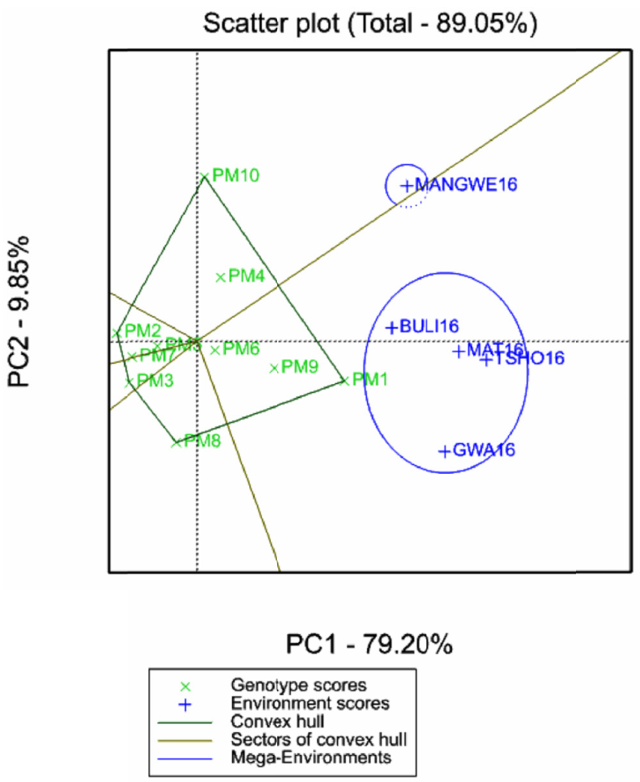

Figure 2. Scatter GGE biplot showing pre-release pearl millet adapted to specific districts, classified within the arid and semi-arid regions in Zimbabwe. Environmental score encompassed in the same blue circle denoted a mega environment and the best genotype for the mega environment is the one positioned on the respective vertex

3.3 Best Pre-release Pearl Millet Genotypes as per Researchers and Farmers' Preferences

The farmers ranked the pre-release lines PM1 and PM9 as the first and second most preferred genotypes, respectively (Table 5). Interestingly, the genotypes that were identified as the most yielding (researcher's preferred trait for selection) and good in terms of grain yield stability (*i.e.*, PM1 and PM9; Figure 1) were also observed as the most favored by the farmers (Table 5). Regression analysis showed a positive and nearly significant relationship between grain yield performance and overall genotype score performance (*i.e.*, farmers' preferences (Figure 3).

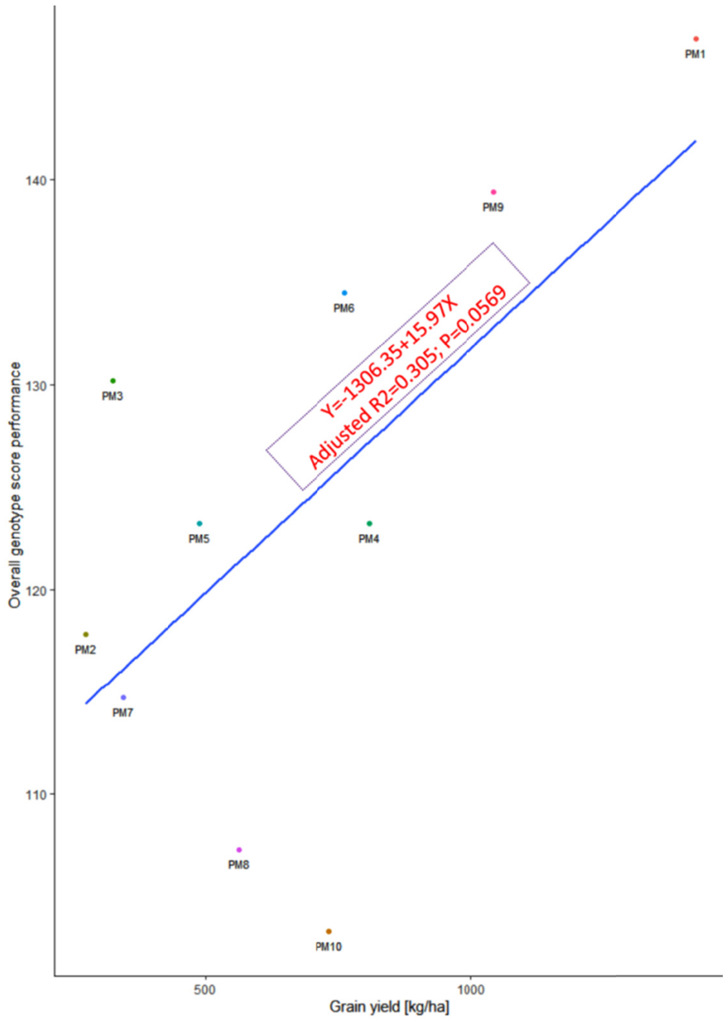

Figure 3. A regression plot showing the relationship between the overall genotype score performance and average grain yield values generated from on-farm pre-release pearl millet trials conducted in Zimbabwe during 2019-20 rainy season

4. Discussion

The Crop Breeding Institute (CBI) developed new pearl millet genotypes that can perform better in the arid and semi-arid regions of Zimbabwe as part of its mandate to increase production in these areas under prevailing conditions. However, plant breeders usually use data from multi-environment trials (METs), the average performance of genotypes in terms of grain yield, and grain yield stability as a basis for the selection of ideal genotypes for the advancement of commercialization. Basing on METs alone is inadequate as they are mainly researcher-managed under optimal conditions, most importantly, without the involvement of farmers who are the end users of the products. Neglecting end users of the product (*i.e.*, farmers) in breeding programs results in market resistance and the poor adoption of newly released varieties by farmers (Witcombe et al., 2005). Therefore, this study aimed to identify genotypes that are high yielding and stable under stress conditions in

Zimbabwe but also possess agronomic attributes most preferred by farmers. The findings from this study indicate high heritability and significant differences in grain yield performance between the pre-release pearl millet genotypes. This indicated the potential to make effective selections within the CBI pearl millet breeding programs because genetic variation and heritability are considered key components for estimating the response to selection in conventional breeding.

The disparity in pearl millet genotype grain yield performance and significant interactions between grain yield and districts calls for the need to identify genotypes that are high yielding and stable for recommendation purposes. Pre-release lines such as PM1 (GY = 1.425 kg ha^{-1}), PM9 (1.043 kg ha^{-1}), and PM6 (GY = 761.8 kg ha^{-1}) can be recommended for release in the arid and semi-arid regions of Zimbabwe, as they are high yielding and stable. These lines can be used in breeding programs as a source of desirable genes. Moreover, farmers preferred these lines (Table 5), suggesting that they were likely to be adopted by farmers. Okashana 1, which is a commercial variety already on market, was found to be high yielding (PM4, GY = 808.8 kg ha^{-1}), stable and ranked fifth in terms of preference by the farmers, can also be used to complement these two new pre-release lines. Findings from a study conducted in Tamil Nadu indicated that on-farm trials offer the possibility to merge modern and traditional plant breeding, thereby promoting the usefulness of new varieties to farmers, especially smallholder farmers working in marginal environments with limited external inputs (Thangapandian et al., 2017). It is important to note that the criteria for selecting ideal genotypes based on stability alone can be precarious, given that some genotypes can be stable but unproductive across environments. For example, in the current study, a pre-release line PM2 was very stable, although it was low yielding at the same time not mostly preferred by farmers. It is logical that farmers did not prefer this pre-release variety despite it being stable, as farmers mainly prioritize food security. Superiority in grain yield performance is a key trait considered by both researchers and farmers when selecting ideal pearl millet varieties. However, the ability of genotypes to consistently produce acceptable yields across different environments indicates their capacity to perform well under various soil and rainfall conditions which is crucial for maintaining productivity in the face of climate change. On the other hand, farmers ranked earliness as their first trait of importance, as early maturing cultivars reach physiological maturity before the rains are gone and can escape bird damage during migration. Similar findings have been reported in on-farm studies conducted in northern Nigeria (Angarawai et al., 2016). Even though conclusions made from this study are not sufficient due to lack of multi seasonal data, it is worth mentioning that outcomes of this multi-centered study represent the initial investigation into farmer perceptions and preferences regarding pearl-millet pre-release lines in Zimbabwe. Therefore, this study can be used to establish foundational findings that can be compared with subsequent pearl millet, on farm trials in the country. The information on farmer's preferences on pearl millet genotypes can be used as immediate feedback that can be incorporated in on-going and future breeding programs to meet the farmers' needs, hence boosting production.

5. Conclusion

In conclusion, merging METs and participatory variety selection strategies may increase the adoption rate of new varieties. In this regard, genotypes PM1, PM6, and PM9, identified as high-yielding, stable, and possessing agronomic traits mostly preferred by farmers, can be promoted for adoption, and may potentially elevate pearl millet productivity in arid and semi-arid regions of SSA.

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Acknowledgments

We greatly appreciate the valuable contributions of Ministry of Lands, Agriculture, Water, Fisheries and Rural Development Extension officers, in mobilizing and providing guidance to farmers who hosted the trials.

Authors Contributions

Dr. C.N. Kamutando and Ms. O. Mukondwa were responsible for study design and revising. Ms. R. Mhuruyengwe was responsible for data collection. Ms. R. Mhuruyengwe and Dr. C.N. Kamutando analyzed the data. Ms. R. Mhuruyengwe drafted the manuscript whereas Dr. C.N. Kamutando, Dr. T.P. Mamphogoro and Ms. O. Mukondwa revised it. All authors read and approved the final manuscript.

Funding

This work was financially supported by the Ministry of Lands, Agriculture, Water, Fisheries and Rural Development in Zimbabwe. The work was also partly funded by the Gastro-Intestinal Microbiology and Biotechnology Unit of the Agricultural Research Council of South Africa.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed Consent

Obtained.

Ethics Approval

The Publication Ethics Committee of the Canadian Center of Science and Education. The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and Peer Review

Not commissioned; externally double-blind peer-reviewed.

Data Availability Statement

The data supporting this study's findings are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data Sharing Statement

No additional data are available.

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