Hindawi
International Journal of Agronomy
Volume 2021, Article ID 9656653, 10 pages
https://doi.org/10.1155/2021/9656653

Research Article

Genotype by Environment Interaction on Grain Yield Stability and Iron and Zinc Content in OPV of Pearl Millet in Ghana Using the AMMI Method

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Received 1 September 2021; Accepted 25 October 2021; Published 8 November 2021

Academic Editor: Vijay Gahlaut

Twenty-two open-pollinated varieties (OPVs) of pearl millet (*Pennisetum glaucum*) genotypes were tested in two locations for three seasons in Ghana to estimate the magnitude of genetic variability, heritability, and stability for grain yield and related traits and grain micronutrients among the varieties. General analysis of variance within and across locations and years revealed very highly significant variability ($p < 0.01$) among the genotypes. The additive main effects and multiplicative interaction (AMMI) analyses revealed significant genotype × environment interaction (GEI) that influenced the relative ranking of genotypes across the environments. Genotypic variance ($\sigma^2 g$) contributed a greater proportion of the phenotypic variance ($\sigma^2 p$) for plant height (530.31) and grain Fe content (34.72). Broad-sense heritability (h^2_{bs}) varied widely from 24.82% for grain yield to 77.53% in days to flower. Phenotypic coefficient of variation (PCV) was higher than genotypic coefficient of variation (GCV) for all traits, indicating strong play of environment on trait expressions. 11 out of the 22 OPVs were stable for grain yield and micronutrients across environments for the three-year period and included GB 8735 and ICMV 221 Wbr and SOSAT-C88.

1. Introduction

Pearl millet research in Ghana has in the past focused on development and deployment of OPVs due to nonavailability of improved OPVs in the system. This has led to the continuous use of landrace by farmers though yields from these have been declining due to recycling of seed [1, 2]. Good knowledge of the nature of genetic variability and heterosis of grain yield and associated traits in pearl millet is important for effective breeding program as current studies point to insufficient information available [3–5]. Again, Bello and others reported that the success of any crop improvement program depends not only on the amount of genetic variation present in a crop but also on the magnitude of variation that is heritable from the parent to the progeny [6]. Also yield as a complex trait is largely influenced by polygenes and environmental factors, hence the need to have an understanding of these components of yield to be able to make meaningful impact in yield studies geared toward improvement [7].

The use of stable genotypes could be a source of yield and mineral enhancement in pearl millet across environments. However, the genotype × environment interaction is a significant feature of plant breeding program as well as the introduction of new crop varieties. Different genotypes of different crop varieties are sensitive to changing soil, climate, and biotic factors as a result of their unique response to each of these factors [8]. It is therefore imperative that the analysis of GEI takes center stage when evaluating varieties for adaptation. Assessment of the stability of grain yield and its associated traits across growing regions is a requirement in breeding for varieties for specific or common environments for high production and productivity. This calls for the development of varieties that would give stable production from year to year and from location to location even under varied conditions of cultivation. It should be noted that selection of varieties based on grain yield alone may not be adequate when GEI is significant [9, 10], especially where these have had frequently changing ranks due to cross interaction in different environments. It is therefore an indispensable fact that the GEI was taken into account, properly understood, and analyzed.

Varied approaches may be deployed for analysis of GEI, some of which are the linear regression model [11] and regression [12]. ANOVA which is an additive model is also used in some cases as it effectively partitions the total sum of squares into the genotype main effect, the environment main effect, and the GEI effect without giving adequate information on the structure of the GEI [13]. The AMMI model has been considered a better alternative model for analysis of GEI in multilocation varietal yield trials as it is more effective and more efficient than other statistical packages [14]. This is because it gives estimate of total GEI effect of each genotype and also partitions the GEI into interaction effects due to environments [15]. This is because the AMMI model combines normal analysis of variance for additive effects with principal component analysis (PCA) for multiplicative structure within the interaction for a better appreciation of the GEI aspect, thereby improving the accuracy of yield estimates and success of selecting genotypes with higher yields [8]. The AMMI model has been effectively deployed in crops such as soybean [16], maize [17], wheat [18], pearl millet [13, 19], and cassava [20, 21] under different environmental conditions. In the current study, the AMMI model was used to determine the nature and scale of GEI effects on selected traits of pearl millet and to identify high yielding and stable OPVs with enhanced grain micronutrients that could serve as alternative for pearl millet farmers in Ghana.

2. Materials and Methods

Two experiments consisting of 22 open-pollenated varieties (OPVs) (Table 1) were established during the 2017, 2018, and 2019 cropping seasons at two locations in the Upper East (CSIR-SARI Manga research station and Denugu close to North East region of Ghana). Five of the OPVs (AFRIBEH-NAARA, NAAD-KOHBLUG, AKAD-KOM, WAAPP-NAARA, and KAANATI) were from Ghana, while the other 17 were received from ICRISAT-Sahelian Centre, Niger.

The experimental site at Manga was disc-harrowed and bullocks were used to raise ridges at 75 cm apart. Plot size was 1.5 m × 3 m (2 rows, 3 meters long) with intrarow spacing maintained at 30 cm for all years. The layout was Randomised Complete Block Design (RCBD) with three replications. N.P.K (15-15-15) fertilizer was applied at the rate of 125 kg/ha immediately after hand weeding, three weeks after sowing, with the hoe. Whole plot was considered for data such as days to 50% flowering, grain yield (kg), Downy mildew incidence (%), and 1000 grain weight (g). The height of five randomly selected plants was measured to determine average plant height (from the base of the plant to the tip of the panicle in cm), panicle length (cm), and girth (cm) at maturity. Seed samples of 30 g/plot were prepared, following the prescribed procedure outlined for grain Zn and Fe density analysis using energy-dispersive X-ray fluorescence (EDXRF) spectrometry method [22, 23].

2.1. Statistical Analysis of Data. Data was subjected to analysis of variance using GenStat software version 12 for individual and combined years to determine the significance of main effect as well as interactions associated with parameters measured. The mean square values from the individual and combined ANOVA tables were used to estimate the phenotypic ($\sigma^2 p$), genotypic ($\sigma^2 g$), and GxE ($\sigma^2 ge$) variances components according to [24] as

$$\begin{aligned} \sigma^2 g &= \frac{\left(\mathrm{MS}_g - \mathrm{MS}_{ge}\right)}{re}, \\ \sigma^2 ge &= \frac{\left(\mathrm{MS}_{ge} - \mathrm{MS}_e\right)}{r}, \\ \sigma^2 e &= \frac{\mathrm{MS}_e}{re}, \\ \sigma^2 p &= \left(\sigma^2 g\right) + \left(\frac{\sigma^2 ge}{e}\right) + \left(\frac{\sigma^2 e}{re}\right). \end{aligned} \tag{1}$$

Estimation of broad-sense heritability (h^2_{bs})was estimated according to [25] as

$$h^2_{bs} = \frac{\sigma^2 g}{\sigma^2 p}, \tag{2}$$

where $\sigma^2 g$ = genotypic variance, $\sigma^2 p$ = phenotypic variance, $\sigma^2 ge$ = genotype × environment variance, $\sigma^2 e$ = pooled error, e = number of environments/years, and r = number of replications.

Expected genetic advance (GA) was calculated as $\mathrm{GA} = K\square_A h^2$; and genetic advance as a percentage of mean (GAM) was calculated as

$$\mathrm{GAM} = \frac{\mathrm{GA}}{\overline{X}} \times 100, \tag{3}$$

and we have K = selection differential (2.06 at 5% selection intensity) according to [26], and $\square_A$ = phenotypic standard deviation.

Genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were determined according to [27] as follows:

$$\begin{aligned} \mathrm{GCV} &= \frac{\sqrt{\sigma^2 g}}{\overline{X}} \times 100, \\ \mathrm{PCV} &= \frac{\sqrt{\sigma^2 p}}{\overline{X}} \times 100, \end{aligned} \tag{4}$$

Table 1: List of hybrids and OPVs used for AMMI stability study.

Genotype	Source	Genotype	Source
AFRIBEH-NAARA	CSIR-SARI, Ghana	MORO	ICRISAT-SC
AKAD-KOM	CSIR-SARI, Ghana	NAAD-KOHBLUG	CSIR-SARI, Ghana
CHAKTI	ICRISAT-SC	SOSAT-C88	ICRISAT-SC
GAMOJI	ICRISAT-SC	SOUNA 3	ICRISAT-SC
GB 8735	ICRISAT-SC	WAAPP-NAARA	CSIR-SARI, Ghana
IBMV 8402	ICRISAT-SC	Faringuero	ICRISAT-SC
ICMV 167005	ICRISAT-SC	ICMV 221	ICRISAT-SC
ICMV IS 85327	ICRISAT-SC	ICMV 167001	ICRISAT-SC
KAANATI	CSIR-SARI, Ghana	ICMV IS 99001	ICRISAT-SC
LCIC 9702 (LCICMV-2)	ICRISAT-SC	ICTP 8203	ICRISAT-SC
LCICMV-4 (Jirani)	ICRISAT-SC	ICMV 167006	ICRISAT-SC

where $\overline{X}$ = grand mean.

GCV and PCV were categorised according to [28] as

$$\text{Low: } < 10\%, \text{ Moderate: } 10 - 20\%, \text{ High: } > 20\%. \quad (5)$$

2.2. Stability Analysis for Grain Yield. Further analysis to determine how stable the genotypes were over the seasons for grain yield was done using the additive main effects and multiplicative interaction (AMMI) model in GenStat version 12 [29] and according to [16]:

$$Y_{ij} = \mu + g_i + e_{ij} + \sum_{K=1}^{n} \lambda_k \alpha_{ik} \gamma_{kj} + e_{ij}, \quad (6)$$

where Y_{ij} is the yield of the i^{th} genotype in the j^{th} year, g_i is the mean of the i^{th} genotype minus the grand mean, λ_k is the square root of the eigenvalue of the PCA axis k, α_{ik} and γ_{kj} are the principal component scores for PCA axis k of the i^{th} genotype and the j^{th} year, respectively, and e_{ij} is the residual. The genotypic environment PCA scores were expressed as unit vector times the square root of λ_k; environment PCA score $= \lambda_k^{0.5} Y_{ik}$; genotype PCA score $= \lambda_k^{0.5} \alpha_{ik}$.

The AMMI stability value for each genotype was calculated as previously described by [30] as

$$\text{ASV} = \sqrt{\left[\frac{\text{IPCA1}_{\text{SQ}}}{\text{PCA2}_{\text{SQ}}} \left(\text{PCA1}_{\text{score}}\right)\right]^2 + \left(\text{IPCA2}_{\text{score}}\right)^2}, \quad (7)$$

where the $\text{IPCA1}_{\text{SQ}}/\text{IPCA2}_{\text{SQ}}$ = the weight derived from dividing the IPCA1 sum of squares value by the IPCA2 sum of squares values from the AMMI analysis of variance table. Larger IPCA scores (positive of negative) indicate that genotype is more adapted to the environment and vice versa [31].

Stability index (SI) for yield rankings based on the AMMI stability value was derived as follows:

$$\text{SI} = \text{RASV} + \text{RY}, \quad (8)$$

where RASV = genotypes ranking based on AMMI stability value and RY = genotype yield ranking across environments; genotypes with low SI values indicate high mean yield stability.

3. Results and Discussion

The mean annual rainfalls at the experimental sites for the four-year period (June to October each year) were 885.3 mm and 871.4 mm for Denugu and Manga, respectively, and indicated a consistent increase in volumes for the period with Denugu recording higher amounts each year except in 2019 where Manga had higher amounts (Table 2). This trend is not surprising because the Denugu site is more south of Ghana than the Manga site. The soils of the sites were well drain and deep to moderate deep (0–30 cm depth). The sites were basically sandy and acidic, with relatively high levels of potassium. Soil pH values of the sites were 5.2 for Denugu and 4.7 for Manga (Table 3). The Fe content was 36.9 mg kg^{-1} for Denugu and 38.5 mg kg^{-1} for Manga, while Zn content was 1.2 mg kg^{-1} and 2.6 mg kg^{-1} for same sites. The agrometeorological data and the soil properties do not differ significantly from earlier reports, especially for the Manga site [31–36], and thus they are ideal for pearl millet crop growth [37–39].

General analysis of variance showed that genotype, environment, and their interactions were highly significant ($p < 0.001$) among the genotypes for all traits (Table 4). The proportions of mean squares for genotype component for traits days to 50% flower, downy mildew incidence, and grain Zn content were higher than the environmental component, indicating that the genotypes responded differently in each location and season. These findings support previous studies on pearl millet at ICRISAT using a recombinant inbred line (RIL) population ICMB 841 × 863B which revealed that genotype × environment interactions were significant for grain yield, flowering time, plant height, and panicle length [40]. Similar reports show that genotype, environment, and their interaction effects influenced significant variation in pearl millet characteristics such as days to flowering, maturity, plant height, 1000-grain weight, grain yield, and seed micronutrients [41–44] and in finger millet [45, 46] which corroborate the current findings.

Genotypic variance ($\sigma^2 g$) contributed a greater proportion of the phenotypic variance ($\sigma^2 p$) of majority of the traits and was 1.4–4.7 times that of the genotype × environment interaction variance ($\sigma^2 g \times e$), indicating wide genetic variations among the genotypes for these traits and confirming the fact that these traits were largely controlled by genetic factors (Table 5). Recent studies reported

Table 2: Mean rainfall for Denugu and Manga sites from June to October for 2016 to 2019 cropping seasons.

Year	Rainfall amount (mm)	
	Manga	Denugu
2016	768.1	888.2
2017	822.4	853.0
2018	894.0	1315.0
2019	1001.0	1140.0
Total	3485.5	4196.2
Average	871.4	1049.1

Table 3: Soil physiochemical properties of experimental fields at a depth of 0–30 cm before establishment of trials at Manga and Denugu in 2016.

Elements tested	Denugu	Manga
Sand (%)	79	80.4
Silt (%)	18	14
Clay (%)	5	5.3
Texture	Loamy sand	Loamy sand
pH	5.2	4.7
Available p (mg kg^{-1})	14.5	15.2
K (mg kg^{-1})	47	35.9
Ca (mg kg^{-1})	0.07	0.06
Mg (mg kg^{-1})	0.06	0.04
Fe (mg kg^{-1})	36.9	38.5
Zn (mg kg^{-1}	1.2	2.6
Organic matter (%)	0.6	0.05

Table 4: Combined analysis of variance for nine traits of 22 pearl millet OPV genotypes evaluated in two locations for three seasons in Ghana.

Source	d.f.	DFF	DMinc	PH	GY	TSW	Fe	Zn
Replication	2	0.283	0.551	1725.4	1306	0.26	0.82	5.55
Genotype (G)	21	588.8***	220.8***	10748.8***	1315549***	24.3***	717.4***	604.2***
Environ (E)	5	97.6***	215.8***	36333.5***	6817833***	68.2***	1170.9***	322.5***
GxE	105	29.8***	23.9***	1203.2***	487608***	4.2***	92.4***	57.3***
Residual	262	3.4	4.23	253.4	83669	1.89	20.34	22.42
Total	395							

*** = significant at $p < 0.001$, DMinc = % downy mildew incidence, DFF = days to 50% flowering, PH = plant height (cm), GY = grain yield (kg/ha), and TGW = 1000-grain weight (g).

similar genotype × environment interaction for pearl millet grains Fe and Zn and sesame [40, 47–49]. In the current studies, $\sigma^2 p$ for grain yield showed that $\sigma^2 g \times e$ was 2.9 times $\sigma^2 g$, indicating that yield is greatly influenced by both genotype and environment interaction, though the environmental component exerted a disproportionally large influence than the genotypic component. This agrees with earlier finding on the importance of genotype × environment interaction in many crop yield studies across environments [47]. Thus, improvement in these traits in these pearl millet OPVs through selection is possible to achieve.

Wide variation existed for broad-sense heritability and ranged from 24.82% for grain yield to 77.53% for days to flowering (Table 5). The values were low for grain yield (˂30%), medium for 1000-grain weight (56.01%) and grain Fe (57.99%), and very high (˃60%) for the other traits. Similar results of high heritability for grain Fe content have been reported by [48]. Although [31] argued that broad-sense heritability alone cannot be relied upon to achieve full genetic gain through selection, [50] maintained that the amount of progress in selection of a trait of interest is influenced by heritability estimates and hence can be relied upon for selection for specific trait improvement. However,

Table 5: Estimates of phenotypic, genotypic, and genotype × environment variability components, broad-sense heritability, and phenotypic and genotypic coefficient of variations for grain yield and other related traits of 22 OPVs in Ghana.

Parameter	DFF	DMinc	PH	GY	TSW	Fe	Zn
$\sigma^2 g$	31.06	10.94	530.31	45996.7	0.01	34.72	30.38
$\sigma^2 g \times e$	8.81	6.57	316.6	134646	0.01	24.02	11.62
$\sigma^2 p$	40.05	17.74	860.99	185291	0.02	59.87	43.25
h^2_{bs}	77.53	61.64	61.59	24.82	56.01	57.99	70.25
PCV	12.29	49.44	14.48	29.69	1.5	18.85	20.83
GCV	10.82	38.82	11.36	14.79	1.12	14.36	17.46
GAM	19.63	62.78	18.37	15.18	1.73	22.51	30.16

$\sigma^2 g$, $\sigma^2 g \times e$, $\sigma^2 p$ = genotypic, genotype × environment, and phenotypic variances, respectively, h^2_{bs} = broad-sense heritability, PCV and GCV = phenotypic and genotypic coefficient of variation, respectively, and GAM = genetic gain as percent of mean.

Adjeben-Danuah and others [20], working on cassava, suggested that, to achieve better results, it is important to combine heritability with the estimation of genetic advance as percent of the mean.

PCV was higher than GCV for all traits (Table 5). 1000-grain weight had low PCV (<10%); days to flowering, plant height, and Fe content had moderate PCV (10–20%), while downy mildew incidence, grain yield, and Zn content had high PCV (>20%). These results are in sync with Govindaraj and others whose work on 61 pearl millet genotypes observed greater PCV than GCV among 15 characters and concluded that these characters were under the influence of environmental factors [44]. Similar results have been reported on earlier works on pearl millet genotypes [51]. The current studies also revealed high estimates of GCV, heritability, and genetic advance for majority of the characters, including Fe and Zn, indicating the significant role of additive gene action in these characters.

The largest expected genetic advance as percent of mean (GAM) was obtained in downy mildew incidence, indicating that close to 70% of this trait could be improved through selection (Table 5) while grain yield, Fe content, and Zn content could be improved by approximately 15.18%, 23%, and 30%, respectively. Although the amount of progress in selection of a trait of interest can be influenced by broad-sense heritability estimates [50], the full genetic potential may not be achieved if this is exclusively relied on during the selection process [31]. The results from this study thus suggest that majority of these traits can be improved using either heritability or GAM.

The genotypes showed significant ($p < 0.05$) varied performances for the individual and combined environments (location and year) for all parameters analysed as observed in Table 6. ICTP 8203 was the earliest to flower (44 days), while ICMV 167005 was the latest to flower (64 days). CHAKTI, GB 8735, ICMV 221, ICTP 8203, and Jirani (all non-Ghanaian varieties) all flowered before 50 days and would therefore be very good substitutes to the Ghanaian genotypes in terms of earliness and other traits including downy mildew incidence.

Mean downy mildew incidence percent varied significantly among the varieties and ranged from 3.80% in SOSAT-C88 to 15.13% in ICMV 221 Wbr. WAAPP-NAARA, ICMV IS 85327, and SOSAT-C88 recorded downy mildew incidence ˂ 5%. Downy mildew is noted as the most dangerous disease of pearl millet. However, reports indicate that the *Iniadi* type with its origin in West Africa is noted to be resistant to the disease [52, 53]. These results corroborate this assertion, since greater majority of the varieties in the current studies recorded low levels of the disease.

Average plant height was significantly different among varieties and ranged from 154.2 cm in ICMV 221 to 260.60 cm in ICMV 167005. Due to the climate change effect that comes with heavy storms during the growing season, shorter or medium plants are preferred by pearl millet farmers to avert lodging [54–56]. CHAKTI, GB 8735, ICMV 221, ICTP 8203, and Jirani recorded average plant heights below 200 cm and are thus useful for the Ghanaian environment to mitigate against lodging.

Average grain yield varied significantly among the varieties, ranging from 963 kg ha^{-1} in CHAKTI to 2035 kg ha^{-1} in SOSAT-C88 in the study. Except AKAD-KOM, all the Ghanaian varieties were similar to the SOSAT C-88 variety. On the average, four Ghanaian and five non-Ghanaian varieties had grain yield between 1516 kg ha^{-1} and 2035 kg ha^{-1}.

The average grain Fe and Zn content ranged between 31.7 mg kg^{-1} and 24.7 mg kg^{-1} in ICMV IS 85327 and between 60.4 mg kg^{-1} and 39.0 mg kg^{-1} in CHAKTI. 10 out of the 22 had grain Fe content more than 40 mg kg^{-1} (ranged from 41.80 to 60.40 mg kg^{-1}) across locations. 8 varieties identified with grain Fe above 40 mg kg^{-1} and grain Zn content above 30 mg kg^{-1} for both locations are considered stable for grain Fe and Zn contents.

AMMI analysis of variance revealed highly significant ($p < 0.001$) effect for genotype, environment, and genotype × environment interaction for all traits (Table 7), indicating that the varieties exhibited variable performance in the tested environments. The genotype effect across environments accounted for a greater proportion of the treatment sum of squares for all parameters studied except grain yield. The interaction effect was strongest (45.34%) for grain yield, while that of genotype was the least (24.47%), suggesting that grain yield is highly influenced by environment and genotype in interaction as alluded to by [20]. Days to 50% flower, plant height, and downy mildew incidence showed that genotype effects accounted for 77.35%, 42.29%, and 56.35% of the sum of squares, respectively, revealing that genotype was strongly influenced by these traits. The first interaction principal component axis (IPCA1) explained 55.30% of the interaction sum of squares for days to 50% flower, 35.85% for downy mildew incidence, and 48.09% for plant height and was significant for these traits.

From Table 7, genotypic effects contributed 64.92% of the treatment sum of squares for grain Fe content, whereas environment and GxE interaction effects contributed 9.47% and 25.61%, respectively. Similarly, genotypic effects accounted for 42.84% of the treatment sum of squares for the grain Zn content but environment and GxE interaction effects contributed 19.11% and 38.05% correspondingly, showing that grain Fe and Zn contents were significantly controlled by genotypes. IPCA1 was significant ($p < 0.001$) and accounted for 39.69% of the GxE interaction sum of squares for grain Fe content and 38.02% of grain Zn content. These results corroborate earlier findings that pearl millet grain Zn content tended to be more sensitive to environmental fluctuation than grain Fe content, an indication of available genes for their substantial improvement through selection [57].

From the AMMI stability value (ASV), the OPVs were ranked based on the least score (Table 8) with a low score representing the most stable genotype. As a result, Moro was ranked the least stable with ASV of 22, while GB 8735 was considered the most stable with an ASV of 1. Relative to grain yield, CHAKTI was the least and SOSAT-C88 was ranked the highest. The yield stability index (YSI) rankings showed that GB 8735 combined high yield with stability, while ICMV 221 Wbr was ranked low with highly stable

TABLE 6: Mean performance of 22 pearl millet OPVs evaluated in two locations over three seasons in northern Ghana.

No.	Genotype	DFF	DM incid (%)	Plant height (cm)	Grain yield (kg ha-1)	1000-seed weight (g)	Grain Fe (mg kg^{-1})	Grain Zn (mg kg^{-1})
1	AFRIBEH-NAARA	44.9	11.7	195.7	1652	10.9	44.6	34.5
2	AKAD-KOM	44.8	9.8	172.4	1318	10.7	52.2	35.8
3	KAANATI	44.7	10.0	198.9	1676	11.1	41.8	31.6
4	NAAD-KOHBLUG	50.9	8.1	217.4	1808	10.6	45.4	32.9
5	WAAPP-NAARA	54.1	4.0	197.1	1599	10.4	33.2	27.5
6	CHAKTI	46.6	12.2	171.5	963	9.9	60.4	39.0
7	Faringuero	54.5	7.1	215.7	1136	10.1	37.0	32.8
8	GAMOJI	59.1	5.8	210.5	1198	9.1	33.3	27.3
9	GB 8735	46.6	13.9	174.8	1608	10.6	52.5	36.5
10	IBMV 8402	53.3	5.2	214.5	1884	7.8	34.3	27.9
11	ICMV 167005	63.7	5.1	260.6	1261	7.6	36.7	30.4
12	ICMV 221	45.1	13.8	154.2	1255	10.2	44.4	36.9
13	ICMV 221 Wbr	52.1	15.1	205.6	1350	9.2	37.7	30.4
14	ICMV IS 85327	55.7	4.5	221.3	1336	8.6	31.7	24.7
15	ICMV IS 99001	56.9	5.3	225.4	1412	8.3	32.0	26.5
16	ICRI-Tabi	53.9	8.8	226.2	1162	8.2	37.6	33.1
17	ICTP 8203	43.7	11.8	188.0	1302	10.5	50.7	38.3
18	LCIC 9702 (LCICMV-2)	49.2	9.4	181.4	1743	9.1	39.6	29.7
19	LCICMV-4 (Jirani)	45.2	10.1	176.4	1516	9.7	43.6	30.8
20	Moro	52.9	5.9	209.7	1297	8.2	48.5	34.9
21	SOSAT-C88	57.1	3.8	221.5	2035	9.6	35.3	27.4
22	SOUNA 3	58.2	6.0	219.9	1390	7.5	30.6	25.8
	Grand mean	**51.5**	**8.5**	**202.7**	**1450**	**9.4**	**41**	**31.6**
	SED	**1.5**	**1.7**	**13**	**236.2**	**1.1**	**3.7**	**3.9**

TABLE 7: Combined AMMI analysis of variance for 22 pearl millet OPV genotypes evaluated for growth and yield related traits in two locations over three seasons in Northern Ghana.

Source		Mean squares						
	d.f.	DFF	DMinc	PH	GY	TSW	Fe	Zn
Treatments	131	122***	62.82***	4074***	861943***	9.85***	289.2***	120.7***
Genotypes (G)	21	588.8***	220.8***	10749***	1315549***	24.26***	1171***	322.5***
Environments (E)	5	97.6***	215.76***	36334***	6817833***	68.18***	717.4***	604.2***
Replication	12	1.6 ns	3.73 ns	400 ns	67178 ns	1.41***	13.7 ns	42.7*
GxE	105	29.8***	23.94***	1203***	487608***	4.2***	92.4***	57.3***
IPCA1	25	69.3***	36.05***	2430***	1277452***	8.08***	154***	91.5***
IPCA2	23	34***	33.26***	1703***	418384***	4.75***	146.5***	89.8***
Error	252	3.5	4.22	258	83801	1.9	20.5	21.3
Source		Sum of squares						
	df	DFF	DMinc	PH	GY	TSW	Fe	Zn
Treatments	131	15986	8229	533725	$1.1E+08$	1291	37880	15809
Genotypes	21	12365	4637	225725	$2.8E+07$	509.4	24590	6773
Environments	5	488	1079	181668	$3.4E+07$	340.9	3587	3021
Replication	12	19	45	4805	806132	16.9	165	513
Interactions	105	3132	2513	126333	$5.1E+07$	440.7	9702	6015
IPCA1	25	1732	901	60755	$3.2E+07$	202	3851	2287
IPCA2	23	782	765	39160	9622827	109.4	3369	2065
Error	252	872	1063	65028	$2.1E+07$	477.8	5167	5373
% treat. SS due to G	21	77.35	56.35	42.29	24.47	39.46	64.92	42.84
% treat. SS due to E	5	3.05	13.11	34.04	30.19	26.41	9.47	19.11
% treat. SS due to GxE	105	19.59	30.54	23.67	45.34	34.14	25.61	38.05
% GxE SS due to IPCA1	25	55.3	35.85	48.09	62.38	45.84	39.69	38.02
% GxE SS due to IPCA2	23	24.97	30.44	31	18.8	24.82	34.72	34.33

*** = significant at $p < 0.001$, ns = not significant ($p > 0.05$), d.f. = degree of freedom, IPCA1 = interaction principal component axis one, IPCA2 = interaction principal component axis two, DMinc = downy mildew percent incidence, DFF = days to 50 percent flowering, PH = plant height (cm), GY = grain yield (kg/ha), and TSW = thousand-seed weight (g).

Table 8: Mean grain yield, AMMI stability values (ASV), and yield stability index (YSI) rankings of 22 OPV pearl millet genotypes pooled across two locations and three seasons in Ghana.

Genotype	Mean grain yield (kg/ha)							
	Mean	Rank (a)	IPCAg [1]	IPCAg [2]	ASV	ASV rank (b)	YSI (a + b)	YSI rank
GB 8735	1608	7	−1.48	−0.25	4.92	1	8	1
WAAPP-NAARA	1599	8	−1.15	6.77	7.77	2	10	2
ICMV 221 Wbr	1350	12	1.22	−9.95	10.74	3	15	3
SOSAT-C88	2035	1	−12.18	−16.75	43.74	15	16	4
SOUNA 3	1390	11	0.2	−19.66	19.67	6	17	5
KAANATI	1676	5	−11.38	1.82	37.8	12	17	6
ICTP 8203	1302	15	4.83	1.33	16.1	5	20	7
IBMV 8402	1884	2	−15.49	−12.58	52.92	18	20	8
ICMV IS 85327	1336	13	7.6	3.98	25.55	8	21	9
LCIC 9702	1743	4	−14.77	5.06	49.29	17	21	10
ICRI-Tabi	1162	20	3.69	2.05	12.43	4	24	11
NAAD-KOHBLUG	1808	3	−21.81	1.83	72.4	21	24	12
AKAD-KOM	1318	14	10.43	0.57	34.63	11	25	13
LCICMV-4 (Jirani)	1516	9	−13.48	3.2	44.85	16	25	14
AFRIBEH-NAARA	1652	6	−21.16	13.97	71.59	20	26	15
Faringuero	1136	21	5.99	7.85	21.37	7	28	16
ICMV 221	1255	18	9.01	3.57	30.12	10	28	17
ICMV IS 99001	1412	10	15.76	−9.53	53.16	19	29	18
ICMV 167005	1261	17	11.45	10.98	39.56	13	30	19
CHAKTI	963	22	7.78	14.56	29.63	9	31	20
GAMOJI	1198	19	12.63	−7.93	42.67	14	33	21
Moro	1297	16	22.29	−0.86	73.98	22	38	22

Table 9: First four AMMI selections of the best mean grain yielding OPVs in each environment.

Environment	Mean	Effect	Rank			
			1	2	3	4
Denugu 17	1522	21.95	Moro	ICMV 167005	WAAPP-NAARA	ICMV IS 99001
Denugu 18	884	21.25	Moro	SOSAT-C88	ICMV IS 99001	WAAPP-NAARA
Denugu 19	1855	−44.8	NAAD-KOHBLUG	AFRIBEH-NAARA	IBMV 8402	SOSAT-C88
Manga 17	1353	11.32	SOSAT-C88	WAAPP-NAARA	LCIC 9702	IBMV 8402
Manga 18	1560	3.72	SOSAT-C88	IBMV 8402	Souna 3	ICMV IS 99001
Manga 19	1526	−13.44	SOSAT-C88	NAAD-KOHBLUG	IBMV 8402	AFRIBEH-NAARA

grain yield. Although IBMV 8402, NAAD-KOHBLUG, and LCIC 9702 were ranked, respectively, 2^{nd}, 3^{rd}, and 4^{th} highest for mean grain yield, the YSI ranking showed that they were 8^{th}, 12^{th}, and 10^{th}, respectively.

Employing the AMMI method of analysis, four highest yielding OPVs in individual environment were identified and selected. SOSAT-C88 was the best selected OPV for the Manga environment for the three seasons and among the best four in the 2018 and 2019 seasons in the Denugu environment (Table 9). ICMV IS 99001, IBMV 8402, and three of the Ghanaian OPVs, namely, NAAD-KOHBLUG, AFRIBEH-NAARA, and WAAPP-NAARA, were selected among the top four in both environments for the three seasons. The results show that 11 OPVs were stable across environments for the three-year period. Moro was ranked best for Denugu in the first two seasons but did not show in any of the other seasons and in Manga. GB 8735 and ICMV 221 Wbr, which were ranked 1^{st} and 3^{rd}, respectively, for YSI were not among the best four selected as the best yielding varieties in any of the environments probably due to their low yields.

4. Association Analysis

Many of the traits studied correlated significantly (either $p < 0.05$ or $p < 0.001$) either positively or negatively with each other (Table 10). Highly significant and positive correlation was observed between grain Fe and Zn contents ($r = 0.914$, $p < 0.001$), plant height, days to 50% flowering ($r = 0.851$, $p < 0.001$), and Downy mildew incidence. Meanwhile, grain Fe and Zn contents highly significantly ($p < 0.001$) and negatively correlated with days to 50% flowering, plant height, and panicle length, and their correlation with 1000-seed weight was highly significantly positive. Grain yield exhibited nonsignificant negative or positive correlation with all the traits studied. Earlier studies on the association of Fe and Zn contents in pearl millet reported very strong positive association between these two micronutrients [47, 58, 59] and this is confirmed in the current studies. This implies that the direct improvement of one of these micronutrients through breeding would invariably lead to the improvement of the other. Again the significant positive correlation of grain Fe and Zn contents

Table 10: Association among yield and its related traits.

	DFF	DMinci	PH	PG	PL	GY	TSW	Fe
DMinci	−0.753**							
PH	0.851**	−0.684**						
PG	−0.291	0.319	−0.481*					
PL	0.706**	−0.528*	0.742**	−0.581**				
GY	−0.063	−0.209	0.055	0.049	−0.058			
TSW	−0.740**	0.518*	−0.631**	0.527*	−0.658**	0.164		
Fe	−0.736**	0.654**	−0.645**	0.292	−0.678**	−0.222	0.547**	
Zn	−0.705**	0.716**	−0.584**	0.253	−0.621**	−0.342	0.537**	0.914**

* and **: significant at $p = 0.05$ and 0.01, respectively, DMinc = % downy mildew incidence, DFF = days to 50% flowering, PH = plant height (cm), GY = grain yield (kg ha^{-1}), and TGW = 1000-grain weight (g).

with downy mildew incidence observed in this study is in sync with earlier reports [58]. Govindaraj and others in 2019 reviewed earlier studies on pearl millet and concluded that the relationship of grain Fe and Zn contents with days to 50% flowering varies with the genetic material used in a study [3].

5. Conclusion

The general analysis of variance for the combined locations showed that genotype, environment, and GxE interactions all showed highly significant ($p < 0.001$) effect for all traits. Genotypic variance ($\sigma^2 g$) contributed a greater proportion of the phenotypic variance ($\sigma^2 p$) of majority of the traits and was 1.4–4.7 times that of the GxE interaction variance ($\sigma^2 g \times e$), indicating wide genetic variations among the genotypes for these traits. Broad-sense heritability for all traits in the combined analysis showed a wide variation from 24.82% to 82.11% with many of them recording medium to high heritability values. The results also showed that a greater proportion of heritability estimates for most of the traits could be improved through selection. Among the non-Ghanaian genotypes, GB 8735, ICMV 221 Wbr, LCICMV-4 (Jirani), LCIC 9702, SOSAT-C88, ICTP 8203, and IBMV 8402 combined high yield with stability and are therefore candidates for further on-station and on-farm evaluation.

Data Availability

The data are currently in the possession of the authors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to express their gratitude to the pearl millet improvement section of the CSIR-Savanna Agricultural Research Institute, Manga station, Ghana, for data collection. They are equally grateful to the pearl millet breeding team of ICRISAT-Niger for providing some of the test materials used in this study and the analysis of grain micronutrient content.

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