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PERFORMANCE OF DUAL-PURPOSE PEARL MILLET GENOTYPES IN WEST AFRICA: IMPORTANCE OF MORPHOLOGY AND PHENOLOGY

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ABSTRACT

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a cereal crop vital for food security in West and Central Africa. Its byproducts also serve as fodder for livestock, especially during dry seasons. The objective of this study was to evaluate selected genotypes from West African pearl millet breeding programmes, for dual-purpose (grain and fodder) and elucidate prospects for future breeding. A total of 83 open-pollinated varieties (OPVs), five composites, six landraces, one synthetic and five hybrids were evaluated at 14 environments in Burkina Faso, Mali, Niger and Senegal during the rainy seasons of 2015 and 2016. Combined analysis of data revealed significant differences among genotypes and prevalence of high genotype-by-environment interaction effects. Two stability analyses models consistently indicated that genotypes 10 (SMILBF10), 14 (SMILBF14) and 39 (SMILML5) were widely adaptable across the region. Plant height, panicle length and panicle yield showed significant positive correlations with grain yield; while days to flowering was negatively correlated. Positive correlation between grain and fodder yields indicate possibility for simultaneous improvement involving the two important traits. This result suggests that germplasm exchange and regionally integrated breeding programmes are important for the identification of widely adapted dual-purpose varieties of pearl millet, particularly in West African drylands.

Key Words: Genotype-by-environment, open-pollinated, *Pennisetum glaucum*

RÉSUMÉ

Le mil à chandelle (*Pennisetum glaucum* (L.) R. Br.) Est une céréale vitale pour la sécurité alimentaire en Afrique de l'Ouest et centrale. Ses sous-produits servent également de fourrage pour le bétail, en

particulier pendant les saisons sèches. L'objectif de cette étude était d'évaluer des génotypes sélectionnés à partir des programmes de sélection du mil à chandelle d'Afrique de l'Ouest, pour l' usage double (céréales et fourrage) et d'élucider les perspectives de sélection dans le future. Les 83 variétés à pollinisation libre (OPV), cinq composites, six variétés locales, une synthétique et cinq hybrides ont été évalués dans les 14 environnements au Burkina Faso, au Mali, au Niger et au Sénégal pendant les saisons des pluies de 2015 et 2016. L' analyse combinée des données ont révélé des différences significatives entre les génotypes et la prévalence des effets élevés d'interaction génotype-par-environnement. Deux modèles d'analyses de stabilité ont systématiquement indiqué que les génotypes 10 (SMILBF10), 14 (SMILBF14) et 39 (SMILML5) étaient largement adaptables dans toute la région. La hauteur de la plante, la longueur de la panicule et le rendement de la panicule ont montré des corrélations positives significatives avec le rendement en grains; tandis que les jours avant la floraison étaient corrélés négativement. Une corrélation positive entre les rendements en céréales et en fourrage indique la possibilité d'une amélioration simultanée impliquant les deux caractères importants. Ce résultat suggère que l'échange de matériel génétique et les programmes de sélection intégrés au niveau régional sont importants pour l'identification de variétés à l' usage double largement adaptées de mil à chandelle, en particulier dans les zones arides d'Afrique de l'Ouest.

Mots Clés: Génotype par environnement, pollinisation libre, *Pennisetum glaucum*

INTRODUCTION

Pearl millet [(*Pennisetum glaucum* (L.) R. Br.) *syn. Cenchrus americanus*] is a dryland cereal crop that plays important roles in subtropical and tropical regions of Africa. Archeological retrievals from different locations of West and Central Africa (D'Andrea and Casey, 2002; Fuller, 2007; Manning *et al*., 2011) and modern evolutionary biology studies using genomic tools, including resequencing of diverse genotypes (Oumar *et al*., 2008; Burgarella *et al*., 2018), revealed that pearl millet originated and is domesticated in the southern periphery of the present Sahara desert in West Africa.

Pearl millet is a highly allogamous (Burton, 1974; Jauhar and Hanna, 1998) and landraces represent genetically heterozygous and heterogeneous open-pollinating populations. Considerable variation in plant morphology and seed characters are noticeable within and between different cultivars. Independent domestication events (Poncet *et al*., 1998), migrations from the centre of domestication, and outcrossing, including intercrossability with close wild relatives are attributable to the high genetic diversity in the germplasm. This huge genetic diversity is a vital resource for the breeding programmes aimed at improving the crop for adaptation, stress tolerance, desirable agronomic traits and yield performance.

Today, pearl millet is cultivated by millions of subsistence farmers as a staple food grain in arid and semi-arid regions of sub-Saharan Africa. It is often the only cereal crop in areas where drought and heat are the limiting factors for the growth and productivity of other cereals such as sorghum or maize. Climate-resilience physiological features of pearl millet at vegetative and reproductive stages make this crop well-suited to grow across a wide range of harsh climatic and edaphic conditions, including limited rainfall, high temperature, low soil fertility and high salinity (Varshney *et al*., 2017).

Variable onset of the rainy seasons, high inter annual rainfall variability, and intermittent droughts during the growing season characterise agricultural features of the Sahelian West Africa (Haussmann *et al*., 2012). Since pearl millet has low water demand and is drought tolerant, its yield can be leveraged for improvement under water-limited environments (Gowda *et al*., 2009). Pearl millet is a C_4 grass with excellent photosynthetic efficiency and biomass production potential (Sanou *et al*., 2012),

which additionally make it the most suitable crop for such harsh environmental conditions.

The area of land planted to pearl millet in the West and Central African region has steadily increased, but average productivity is still low, rarely reaching 1000 kg ha^{-1} (Diack *et al*., 2017). This is attributed to limited genetic improvement, poor crop management practices and unfavourable socio-economic conditions of the subsistence farmers growing the crop. Farmers predominantly grow inherently low yielding landraces that are adaptable to specific agroclimatic niches and soil fertility conditions. Because of limited resource allocation, pearl millet improvement research is not in pace with the demand for the crop as well as the extent of production constraints. To develop and deliver improved varieties that withstand the biotic and abiotic stresses limiting productivity of the crop in the region are urgently needed. Therefore, a regionally integrated research strategy is encouraged for effective germplasm and information exchange for comparative advantage of the pearl millet breeding programmes in the region.

The objective of this study was to evaluate selected genotypes developed in West Africa for dual-purpose (grain and fodder) production and to elucidate the prospect of regional breeding.

MATERIALS AND METHODS

Experimental materials. A total of 100 pearl millet accessions, comprising of open pollinated varieties (OPV), composites and synthetic varieties, as well as experimental hybrids were used (Table 1) in this study. The accessions were contributed by pearl millet breeding programmes of Burkina Faso (34), Mali (20), Niger (23) and Senegal (23).

Testing locations. The test locations were systematically selected in each of the four countries, to represent both the Sahelian and Sudanian zones where pearl millet is predominantly grown. The rainfall characteristics of the test locations during 2015 and 2016 growing seasons are presented in Table 2; the only exception was that of N'Tarla (Mali) which had no weather data.

The field trials were conducted at seven locations in the four countries; during 2015 and 2016 growing seasons. The test locations were Dori in Burkina Faso, Cinzana and N'Tarla in Mali, Bengou and Maradi in Niger, and Bambey and Nioro in Senegal. The experiment was laid out in a randomised complete block design (RCBD), with two replications. Each accession was planted in two-row plots of 4 m and 0.8 m inter- and intra-row spacings. All the recommended agronomic practices at each location were applied. Data were collected on days to flowering (DFL), plant height (PHT), number of panicles per plot (NPL), panicle length (PLG), panicle yield (PNY), grain yield (GYD), and fodder yield (FYD).

Statistical analysis. Phenotypic data were analysed using the SAS 9.4 ® statistical programme (SAS Institute, Cary, NC) and R package called Performance Analytics. Normality for each trait was determined using the univariate procedure. An initial analysis of variance was performed for each environment to verify the existence of differences among the accessions. The homogeneity between residual variances was determined, and a combined analysis of variance was used to test the genotype and environment effects and the magnitude of the G×E interaction. A generalised linear model was used to partition the variances into year, location, replication, genotype and their interaction effects for each trait. Statistical significance was assessed at 5% probability level, unless indicated otherwise.

Stability analysis. Two stability analysis models were used to determine grain yield performance of the genotypes across environments. Both the Additive Main Effects and Multiplicative Interactions (AMMI) analysis (Gauch and Zobel, 1988) and Eberhart and Russell stability parameters (Eberhart and

TABLE 1. List of accessions used in the study with their pedigree, and source country

No	Entry	Designation	Variety (type)*	Country
1	SMILBF1	PE05887	Var exp (OPV)	Burkina Faso
2	SMILBF2	KalpelgaxPE03922	Var exp (OPV)	Burkina Faso
3	SMILBF3	PE0437xPE00515	Var exp (OPV)	Burkina Faso
4	SMILBF4	PE00397xPE00515	Var exp (OPV)	Burkina Faso
5	SMILBF5	MISARI-1	OPV	Burkina Faso
6	SMILBF6	MISARI-2	OPV	Burkina Faso
7	SMILBF7	PE05578 C1	Var exp (OPV)	Burkina Faso
8	SMILBF8	PE08030 C0	Composite C0	Burkina Faso
9	SMILBF9	PE08011 C0	Composite C0	Burkina Faso
10	SMILBF10	Local Djibasso C0	Composite C0	Burkina Faso
11	SMILBF11	Sahel 22 C0	Composite C0	Burkina Faso
12	SMILBF12	PE00967 C0	Composite C0	Burkina Faso
13	SMILBF13	IKMP 1	OPV	Burkina Faso
14	SMILBF14	IKMP 5	OPV	Burkina Faso
15	SMILBF15	IKMV8201	OPV	Burkina Faso
16	SMILBF16	PE01203 X PE05980-R3	Var exp (OPV)	Burkina Faso
17	SMILBF17	PE02987 X ICMV IS 92222	Var exp (OPV)	Burkina Faso
18	SMILBF18	PE02853xPE00404 R3	Var exp (OPV)	Burkina Faso
19	SMILBF19	Group1	Var exp (OPV)	Burkina Faso
20	SMILBF20	Group3	Var exp (OPV)	Burkina Faso
21	SMILBF21	Group4	Var exp (OPV)	Burkina Faso
22	SMILBF22	Group6	Var exp (OPV)	Burkina Faso
23	SMILBF23	Groupe7	Var exp (OPV)	Burkina Faso
24	SMILBF24	Local kamboinse	local	Burkina Faso
25	SMILBF25	Local Nahartenga	local	Burkina Faso
26	SMILBF26	GBxMORO	Var exp (OPV)	Burkina Faso
27	SMILBF27	PE00437XPE00273	Var exp (OPV)	Burkina Faso
28	SMILBF28	PE00437XICMVIS92222	Var exp (OPV)	Burkina Faso
29	SMILBF29	PE00397XPE00404	Var exp (OPV)	Burkina Faso
30	SMILBF30	PE02987XPE05347	Var exp (OPV)	Burkina Faso
31	SMILBF31	PE053/73	Parent R (OPV)	Burkina Faso
32	SMILBF32	IBMV8402	OPV	Burkina Faso
33	SMILBF33	ICMVIS89305	OPV	Burkina Faso
34	SMILBF34	PE05539	Var exp (OPV)	Burkina Faso
35	SMILML1	CzSyn 00-06	Synth (OPV)	Mali
36	SMILML2	SoSat	OPV	Mali
37	SMILML3	CzSyn 00-01	Synth (OPV)	Mali
38	SMILML4	CzSyn 03-10	Synth (OPV)	Mali
39	SMILML5	CzSyn 00-02	Synth (OPV)	Mali
40	SMILML6	Cr Toroniou HTC	hybrid	Mali
41	SMILML7	CzToroniou HTC Aristé	hybrid	Mali
42	SMILML8	Cz Maïwa HTC aristé	hybrid	Mali
43	SMILML9	Toroniou C1	OPV	Mali
44	SMILML10	Sanioba 03	OPV	Mali
45	SMILML11	Indiana 05	OPV	Mali

TABLE 1. Contd.

No	Entry	Designation	Variety (type)*	Country
46	SMILML12	Djiguifa	OPV	Mali
47	SMILML13	CzMil Aristé	Synth (OPV)	Mali
48	SMILML14	NKO/TC1	OPV	Mali
49	SMILML15	Boboni	OPV	Mali
50	SMILML16	Cz Syn 03 11	Synth (OPV)	Mali
51	SMILML17	16	Var exp (OPV)	Mali
52	SMILML18	PEO6001	OPV	Mali
53	SMILML19	PE02983	OPV	Mali
54	SMILML20	PE05607	OPV	Mali
55	SMILNG1	IP8688	Var exp (OPV)	Niger
56	SMILNG2	PE02945	Var exp (OPV)	Niger
57	SMILNG3	B9-Tabi	OPV	Niger
58	SMILNG4	PE02831	Var exp (OPV)	Niger
59	SMILNG5	PE00040	Var exp (OPV)	Niger
60	SMILNG6	PE05913	Var exp (OPV)	Niger
61	SMILNG7	PE00626	Var exp (OPV)	Niger
62	SMILNG8	PE05346	Var exp (OPV)	Niger
63	SMILNG9	PE01491	Var exp (OPV)	Niger
64	SMILNG10	PE02898	Var exp (OPV)	Niger
65	SMILNG11	PE02603	Var exp (OPV)	Niger
66	SMILNG12	PE05387	Var exp (OPV)	Niger
67	SMILNG13	PE00437	Var exp (OPV)	Niger
68	SMILNG14	PE00456	Var exp (OPV)	Niger
69	SMILNG15	PE02983	Var exp (OPV)	Niger
70	SMILNG16	PE08039	Var exp (OPV)	Niger
71	SMILNG18	GAMOGI	Landrace (OPV)	Niger
71	SMILNG17	HKP-GMS x MORO	OPV x Landrace	Niger
73	SMILNG19	GA x HKB	Landrace x OPV	Niger
74	SMILNG20	BOUDOUMA	Landrace (OPV)	Niger
75	SMILNG21	TTCHININ-BIJINI	Landrace (OPV)	Niger
76	SMILNG22	HKB	OPV	Niger
77	SMILNG23	H80-10GR	OPV	Niger
78	SMILSG1	S1-516	Landrace (OPV)	Senegal
79	SMILSG2	S1-308	Landrace (OPV)	Senegal
80	SMILSG3	S1-433	Landrace (OPV)	Senegal
81	SMILSG4	S1-86	Landrace (OPV)	Senegal
82	SMILSG5	S1-619	Landrace (OPV)	Senegal
83	SMILSG6	S1-328	Landrace (OPV)	Senegal
84	SMILSG7	S1-55	Landrace (OPV)	Senegal
85	SMILSG8	S1-59	Landrace (OPV)	Senegal
86	SMILSG9	S1-126	Landrace (OPV)	Senegal
87	SMILSG10	S1-215	Landrace (OPV)	Senegal
88	SMILSG11	S1-416	Landrace (OPV)	Senegal
89	SMILSG12	S1-523	Landrace (OPV)	Senegal
90	SMILSG13	S1-510	Landrace (OPV)	Senegal

TABLE 1. Contd.

No	Entry	Designation	Variety (type)*	Country
91	SMILSG14	S1-515	Landrace (OPV)	Senegal
92	SMILSG15	S1-423	Landrace (OPV)	Senegal
93	SMILSG16	S1-28	Landrace (OPV)	Senegal
94	SMILSG17	S1-53	Landrace (OPV)	Senegal
95	SMILSG18	S1-527	Landrace (OPV)	Senegal
96	SMILSG19	S1-323	Landrace (OPV)	Senegal
97	SMILSG20	S1-169	Landrace (OPV)	Senegal
98	SMILSG21	S1-620	Landrace (OPV)	Senegal
99	SMILSG22	S1-633	Landrace (OPV)	Senegal
100	SMILSG23	THIALACKZ	Synth OPV	Senegal

TABLE 2. Monthly total rainfall (mm) of the trial locations during 2015 and 2016 growing seasons at the different study sites in west and central African countries

Location	Year	May	June	July	August	September	October	Total rainy days
Maradi, Niger	2015	0.9	34.4	168.1	228.6	64.9	0.0	35
	2016	24.0	49.0	175.0	210.5	90.5	0.0	37
Bengou, Niger	2015	19.3	53.5	180.2	277.3	236.0	30.0	56
	2016	97.5	101.3	163.3	272.9	123.1	17.0	74
Bambey, Senegal	2015	0.0	0.0	124.0	281.1	265.6	21.5	39
	2016	-	0.0	116.4	136.9	150.0	9.2	34
Nioro, Senegal	2015	0.0	1.7	142.6	363.3	342.3	164.6	55
	2016	0.5	21.3	240.3	327.4	314.2	13.5	52
Dori, Burkina Faso	2015	0	76	83.5	48.5	2.5	0	8
	2016	32.5	65.5	139	160.5	67	6.5	27
Cinzana, Mali†	2015	40	104	182	234	132	38	-
	2016	40	104	182	234	132	38	-

† Mean rainfall data of 10 years (2005 to 2015) at Cinzana, Mali. Local agroclimatic data was not available for N'tarla in Mali

Russell, 1966) were conducted using GEA-R (Genotype x Environment Analysis with R for Windows) Version 4.1 (Pacheco *et al*., 2018).

AMMI was used to adjust the main or additive genotype and environmental effects by analysis of variance, in addition to the adjustment of the multiplicative effects for the G×E interaction by principal component analysis. The multi-environment performance analysis was conducted according to the following AMMI statistical model:

$$Y_{ge} = \mu+\alpha_g+\beta_e+\Sigma_n\lambda_n\gamma_{gn}\delta_{en}+p_{ge}$$ (Gauch, 1988)

Where:

Y_{ge} is the yield of genotype g in environment e, ì is the grand mean, α_g is the genotype deviation from the grand mean, β_e is the environment deviation from the grand mean, λ_n is the singular value for the interaction principal component and correspondingly λ_{2n} is its eigenvalue, γ_{gn} is the eigenvector value for genotype g and component n, δ_{en} is the eigenvector value for environment e and component n, with both eigenvectors scaled as unit vectors, and p_{ge} is the residual.

The interaction scores are scaled as $\lambda_{0.5n}\gamma_{gn}$ and $\lambda_{0.5n}\delta_{en}$ so that their products estimate interactions without the need of yet another multiplication by λ.

The sum of squares of the G×E interaction for grain yield was divided into a *n* singular axis or interaction principal component axis (IPCA), which reflects the standard portion in which each axis corresponded to a particular AMMI model. Selection of a model that best describes the GEI was based on the F_R test, as proposed by Cornelius *et al.* (1992) to determine how many IPCs are significant. When the F_R test is significant, it suggests that there is at least one more multiplicative term in addition to the terms already fitted.

Furthermore, AMMI's stability value (ASV) was calculated in order to rank genotypes in terms of stability using the formula suggested by Purchase (Purchase *et al.,* 2000). The smaller ASV indicates a more stable genotype across environments; and the larger the ASV the more specifically adapted the genotype is to a certain environment.

The Eberhart and Russell stability analysis model states as follows:

$$\gamma_{ij} = \mu + d_i + \varepsilon_j + g_{ij} + \varepsilon_{ij}$$ (Eberhart and Russell, 1966)

Where:

γ_{ij} is the yield estimate of the i^{th} genotype in the j^{th} environment, μ is grand mean of overall genotypes and environments; d_i is an additive genetic contribution of the i^{th} genotype; ε_j is additive environmental contribution of the j^{th} environment; g_{ij} is the genotype-environmental interaction of the i^{th} genotype in the j^{th} environment; ε_{ij} is experimental error of the i^{th} line in the j^{th} environment.

RESULTS AND DISCUSSION

Agronomic and yield traits

Days to 50% flowering. Days to 50% flowering (DFL) for accessions revealed that SMILSG10 took the longest time (81 days) to flower; followed by SMILNG4, SMILSG19, SMILNG12, and SMILNG13 in that order. On the other hand, 22 accessions took less than 60 days to flower. The early flowering genotypes were SMILBF15 (56 days), SMILNG20 (56 days), and SMILNG17 (58 days). Mean DFL was less than 60 days at Bambey in 2016, Nioro in 2016, and Dori in 2016. Cinzana in 2015, N'tarla in 2015, and Maradi in 2016 had longer mean DFL and several genotypes 100 days (data not presented). Pearl millet landraces are diverse in morphology, cycle duration, yield potential, and stress tolerance.

Based on days to flowering, pearl millet cultivars grown in West Africa are predominantly categorised into *Souna* (early-flowering) and *Sanio* (late-flowering) morphotypes (Dussert *et al.*, 2015). This phenological diversity contributed to the adaptation of the crop to the Sahel zone, which is characterised by inter- and intra-annual rainfall fluctuations. The short seasoned and photoperiod insensitive *Souna* morphotypes are adaptable to the short rainy season of the Sahel. The late flowering *Sanio* are more sensitive to photoperiod and adapted to the Sudanian zone, and have higher grain, as well as fodder yield potential than early-flowering ones (Haussmann *et al.*, 2007). Therefore, flowering time is an important trait in pearl millet adaptation to climate variability and genetic yield potential.

The flowering date of the genotypes was shortened in the severe drought conditions at Bambey in 2016, Nioro in 2016, and Dori in 2016. In Maradi in 2016, Cinzana in 2015, and N'tarla in 2015 longer mean DFL was recorded probably because of better rainfall amount and distribution. This result indicates that the long duration genotypes, with high biomass production potential, have the drought escape mechanism. The drought avoidance mechanism that delays the development of tillers to prolong flowering time is more prevalent in the short duration *Souna* ecotypes (Winkel *et al.*, 1997).

Plant height. There were significant differences between years, among locations and accessions for plant height (PHT) and interaction effects, except for location × genotype (Table 3). PHT was significantly greater in 2015 (276 cm) than 2016 (247 cm). Location-wise, plant height was high at Maradi (292) and Bengou (304) in 2015; while it was short at Dori (206 cm) and N'tarla (237 cm) in 2015 (data not presented). The tallest overall PHT was in SMILNG15 (299 cm); while the shortest was SMILBF32 (217 cm).

Plant height is a growth attribute directly linked with the productive potential of a genotype, especially in terms of fodder yield (Maleko *et al.*, 2019). Reports indicate significant differences among pearl millet cultivars in respect to plant height (Amodu *et al.*, 2007; Hassan *et al.*, 2014). In spite of the inherent genetic differences prevalent among the genotypes, the results of this study revealed that plant height was highly influenced by the environment. The dry conditions in the Sahel significantly reduced plant height of the genotypes studied.

Panicle length. Panicle length (PLG) was significant across environments, genotypes and interactions, except for location × genotype (Table 2). Accessions with the longest panicle included SMILNG21,

TABLE 3. Combined analysis of variance for agronomic and yield traits of 100 pearl millet accessions grown at multi-environments in Burkina Faso, Mali, Niger and Senegal during 2015 and 2016

Source	DF	F-value						
		DFL	PHT	PLG	NPL	PNY	GYD	FYD
Year (Y)	1	88.9**	568.06**	4.82*	218.44**	1293.15**	346.77**	345.53**
Location (L)	6	457.76**	190.78**	19.87**	262.01**	420.83**	110.83**	331.27**
Replication	1	0.25ns	1.1ns	3.88ns	0.02ns	4.12*	0.38ns	34.53**
Genotype (G)	99	31.01**	10.58**	25.4**	5.41**	2.42**	4.54**	3.92**
Y x L	6	200.75**	77.29**	22.32**	60.74**	223.41**	69.5**	28.41**
Y x G	98	8.57**	2.65**	1.58**	2.12**	1.89**	1.86**	2.32**
L x G	592	1.78**	1.09ns	1.07ns	1.48**	1.42**	2.3**	1.2**
Y x L x G	573	1.34**	0.96ns	1.15*	1.15*	1.48**	1.4**	1.18*
Error DF		1346	1347	1339	1298	1196	1348	1030
R^2		0.88	0.78	0.76	0.78	0.85	0.76	0.81
CV (%)		7.8	12.0	19.8	30.4	32.3	33.8	40.9
Root MSE		5.1	31.3	8.6	15076.7	1003.9	523.5	1499.7
Mean		65 days	262 cm	43 cm	49614	3109 kg ha^{-1}	1548 kg ha^{-1}	3664 kg ha^{-1}

DFL = Days to 50% flowering; PHT = Plant height (cm); PLG = Panicle length (cm); NPL = Number of panicles per hectare; PNY = Panicle yield (kg ha^{-1}); GYD = Grain yield (kg ha^{-1}); and FYD = Fodder yield (kg ha^{-1}); DF = degrees of freedom, CV = Coefficient of variation; MSE = Mean Square of Error; ns = not significant; *, **, = significant at P< 0.05 and P<0.01 probability levels, respectively

SMILSG1 and SMILSG12, with mean PLG values of 69, 63 and 62 cm, respectively. On the contrary, eight accessions (SMILBF26, SMILNG20, SMILBF25, SMILBF2, SMILBF24, SMILBF15, SMILNG3 and SMILML2) had low PLG values, which ranged from 28 to 33 cm.

Panicle length is one of the major yield components in pearl millet (Ouendeba *et al*., 1995; Obeng *et al*., 2012) and landraces grown in West Africa are diverse in panicle size (Wilson *et al*., 1990; Ouendeba *et al*., 1995; Upadhyaya *et al*., 2017). The diversity available in the landraces for this important yield component and its correlation with grain and fodder yields (Diack *et al*., 2017) can be leveraged for dual-purpose cultivar development in West Africa.

Number of panicles. There were significant differences among years, locations, genotypes and their interactions for number of panicles (NPL) per hectare (Table 3). The result showed that SMILBF25, followed by SMILBF13, SMILBF24 and SMILBF30 produced significantly ($P<0.001$) higher mean NPL (64497, 62640, 62230 and 60908 panicles per hectare, respectively). However, two of these accessions (SMILBF25 and SMILBF24) had short panicles. SMILNG4 and SMILNG16 showed the lowest mean NPL of 34473 and 34654 per hectare. Lower NPL values were observed at Dori and N'tarla, which reflected limited tillering attributable to drought stress. Number of panicles (NPL) per unit area is an indicative of the stand count and productive tillers in pearl millet, and has direct effect on both grain and fodder yields. Moreover, genotypes with good tillering capacity and uniform maturity are important in bolstering both grain and fodder yields. A previous report indicates that competition for light between axes, especially during stem elongation stage suppress the growth of productive tillers (Oosterom *et al*., 2001). Therefore, enhancing the number of productive tillers depends on leaf area profiles of the main shoots and tillers. Tillering is also a very plastic trait that can adapt to environmental conditions and crop management. Selection of genotypes with good stand establishment, early uniform tiller formation, and uniform maturity may boost dual-purpose productivity of the crop.

Panicle yield. Panicle yield (PNY), the main selection index for grain yield in pearl millet (Haryanto *et al*., 1998), was highly significant across the environments, genotypes and their interaction effects for PNY (Table 3). Accessions with significantly high PNY included SMILNG9 (3734 kg ha^{-1}) and SMILML6 (3600 kg ha^{-1}). On the other hand, the lowest PNY values were observed for SMILNG3 (2137 kg ha^{-1}) and SMILNG1 (2206 kg ha^{-1}) that also had short PLG.

Panicle yield comprises of the individual panicle size and number of panicles per unit area (Fageria, 2007). Therefore, the length and diameter of the panicle, number of panicles, and grain filling, as well as seed size and plumpness are reflected in panicle yield. Panicle yield was reported to show highly positive response to selection with high heritability (Haryanto *et al*., 1998). Therefore, in selection for dual-purpose varieties, due consideration should be given to panicle yield as a favourable trait.

Grain yield. Grain yield (GYD) was significant between years, across locations, among genotypes and their interactions (Table 3). The accession with highest mean GYD was SMILBF9 (1989 kg ha^{-1}), followed by SMILML6 (1975 kg ha^{-1}) and SMILSG1 (1904 kg ha^{-1}). Fourteen other accessions had mean GYD greater than 1800 kg ha^{-1}. On the other hand, 11 accessions had overall mean GYD less than 1300 kg ha^{-1}.

All the interaction effects were also significant, implying the difficulty to select the genotypes based on their mean performance *per se*. This performance outcome calls for stability analysis to select the most adaptable genotype with stable performance across environments or select narrowly adapted genotypes for a specific environment.

Otherwise, grain yield improvement and its stable performance across locations and over years are important in plant breeding and thus needs greater exploration to benefit different national breeding programmes in the Sahel region.

Fodder yield. Fodder yield (FYD) also showed significant differences between years, across locations, among genotypes and their interactions (Table 3). Overall, two locations in Niger (Maradi and Bengou) showed higher FYD than the other locations. Accessions SMILNG11, SMILBF5, SMILNG15, SMILML16 and SMILBF12 had significantly higher overall FYD that ranged from 4620 to 4648 kg ha^{-1}. On the contrary, there were genotypes with FYD lower than 2000 kg ha^{-1}.

Previous studies showed prevalence of significant differences among pearl millet landraces in total biomass, grain and stover yields (Yadav and Bidinger, 2008); all of which are vital resources for crop improvement as it offers an opportunity for selection of a desired genotype as a potential cultivar. The higher the extent of genetic variability in the breeding population, the more likelihood of improvement for targeted traits. Therefore, landraces may serve as the main sources of variation for breeding dual-purpose varieties and other desirable traits. Furthermore, the landraces showed significant heterosis for biomass, grain and stover yields (Yadav and Bidinger, 2008). Thus, landrace-based topcross hybrids may be a better alternative to the OPV in dual-purpose variety development in the region.

G×E interaction and yield stability. The combined analysis of variance (Table 3) showed presence of highly significant GEI for yield that does not permit to define overall ranking of varieties across environments. The result of performance evaluation at seven locations, for two year (14 total environments) across the region, indicated evidence of widely adaptable genotypes among the accessions. There were also genotypes with specific adaptation, as their yield performance was favoured in certain environments mainly in relatively due to favourable rainfall conditions. Since GEI was high, the stability of the test genotypes was estimated by two yield stability parameters, namely Eberhart and Russell (Eberhart and Russell, 1966) and the Additive Main effects and Multiplicative Interaction (AMMI) model (Gauch, 1988) and the outcomes are discussed in the following sections.

Eberhart and Russell stability analysis. In this stability analysis, the sum of square due to G × E were apportioned into individual genotypes (X-i), regression of environmental means (bi) and deviation from regression (S^2d). The regression coefficients (bi) and mean square deviation from regression (S^2d) were used to define genotype stability. The Eberhart and Russell stability analysis and the graph of regression of environmental means (bi) against the deviation from regression commonly called coefficient of determination (S^2d) (Fig. 1), identified 10 genotypes which had general adaptability (no significant change in their yields as a result of changes in climatic conditions in the test environments). These were entries number 10 (SMILBF10), 14 (SMILBF14), 39 (SMILML5), 57 (SMILNG3), 58 (SMILNG4), 65 (SMILNG11), 76 (SMILNG22), 78 (SMILSG1), 79 (SMILSG2), and 94 (SMILSG17). Among these generally adaptable genotypes, SMILBF10 and SMILBF14 were contributed by Burkina Faso. SMILSG1, SMILSG2 and SMILSG17 by Senegal; while SMILNG3, SMILNG4, SMILNG11 and SMILNG22 were from Niger, and SMILML5 from Mali breeding programmes. From this result, we deduce that regional germplasm exchange is vital in identifying widely adaptable pearl millet cultivars in the region.

AMMI analysis. The environment effect explained almost a third (32.5%) of the variation in grain yield performance across environments (Table 4). Genotype explained only 10.7 % of the variation; while the G x E

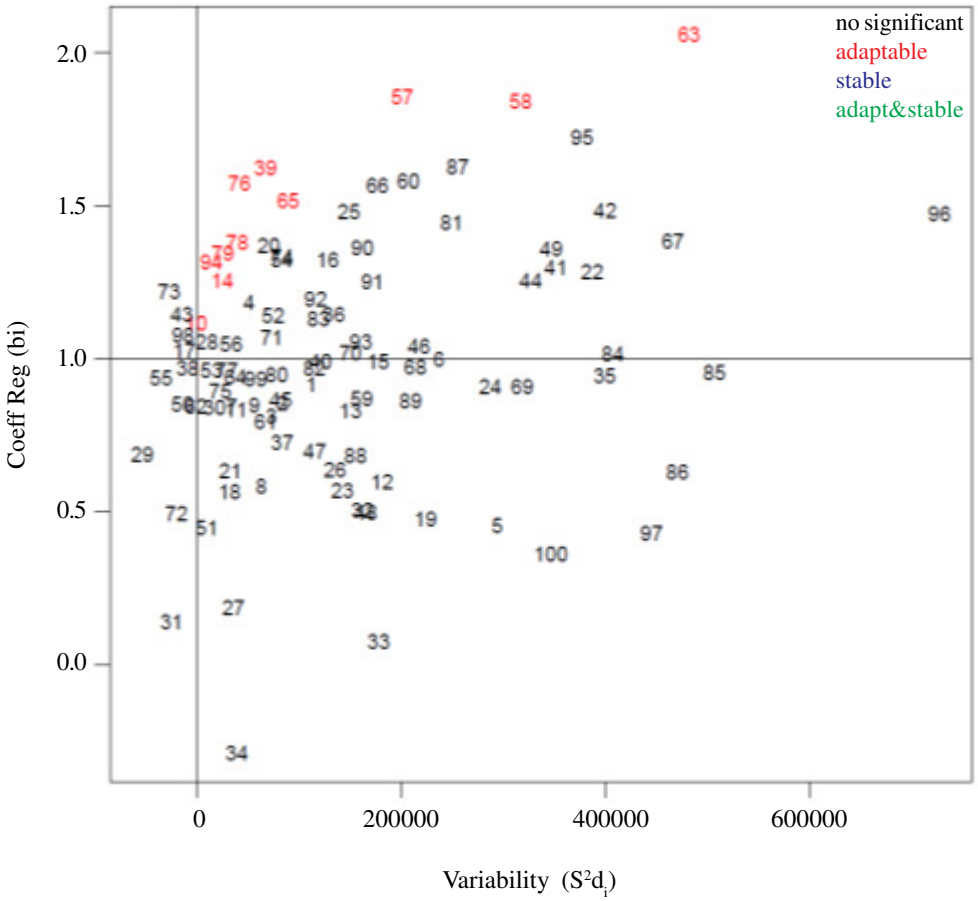


Figure 1. Eberhart and Russell stability plot of 100 pearl millet genotypes based on regression (bi) and deviations from regression (S2di). Entries with the red color are identified as widely adaptable.

component of the variation accounted for 56.8%. Though the first three axes explained a total of 55.10 % of the interaction effect for grain yield, seven PCs were significant and accounted for 81.7 % of the interaction sum of squares. This implies that there are multiple factors contributing to the interaction effects. The PCA analysis indicated year-to-year that variations in those locations, to the level it affects the yield performance of the genotypes.

On the basis of Factor 1, test locations Nioro and Bambey consistently belonged to a similar category, but differed on the basis of Factor 2 (Fig. 2). Genotypes such as 84 (SMILSG7), 85 (SMILSG8), 93 (SMILSG16), 95 (SMILSG18), and 97 (SMILSG20) better adapted to Nioro and Bambey. On the other hand, Dori, Bengou, Maradi, N'tarla and Cinzana were classified as similar growing environments. Genotypes 8 (SMILBF8), 23 (SMILBF23), 29 (SMILBF29), 35 (SMILML1) and 46 (SMILML12) were better adapted to this set of locations.

In the resulting Factor 1 against grain yield biplot, contemporarily main effects (genotypes and environments average yields) and interaction were distributed throughout the four sections of the biplot (Fig. 3). The GGE biplot revealed that genotype such as 40 (SMILML6), 41 (SMILML7), 78 (SMILSG1) and 91 (SMILSG14) had overall high mean grain yield and responsive performance as they

TABLE 4. Analysis of variance for pearl millet grain yield and G X E partitioning according to the Additive Main Effect and Multiplicative Interaction (AMMI) analysis

Source	DF	Variation explained (%)	% explained (cumulative)	F-Ration	P value
Environment (E)	13	32.5	32.5	116.65	0.00
Genotype (G)	99	10.7	43.2	5.06	0.00
EXG	1287	56.8	100.0	2.06	0.00
PC1	111	25.5	25.5	6.09	0.00
PC2	109	16.4	41.9	3.99	0.00
PC3	107	13.2	55.1	3.29	0.00
PC4	105	9.0	64.1	2.27	0.00
PC5	103	6.9	71.0	1.79	0.00
PC6	101	5.7	76.7	1.49	0.00
PC7	99	5.0	81.7	1.34	0.02
Residuals	1399	0.0	0.0	-	-

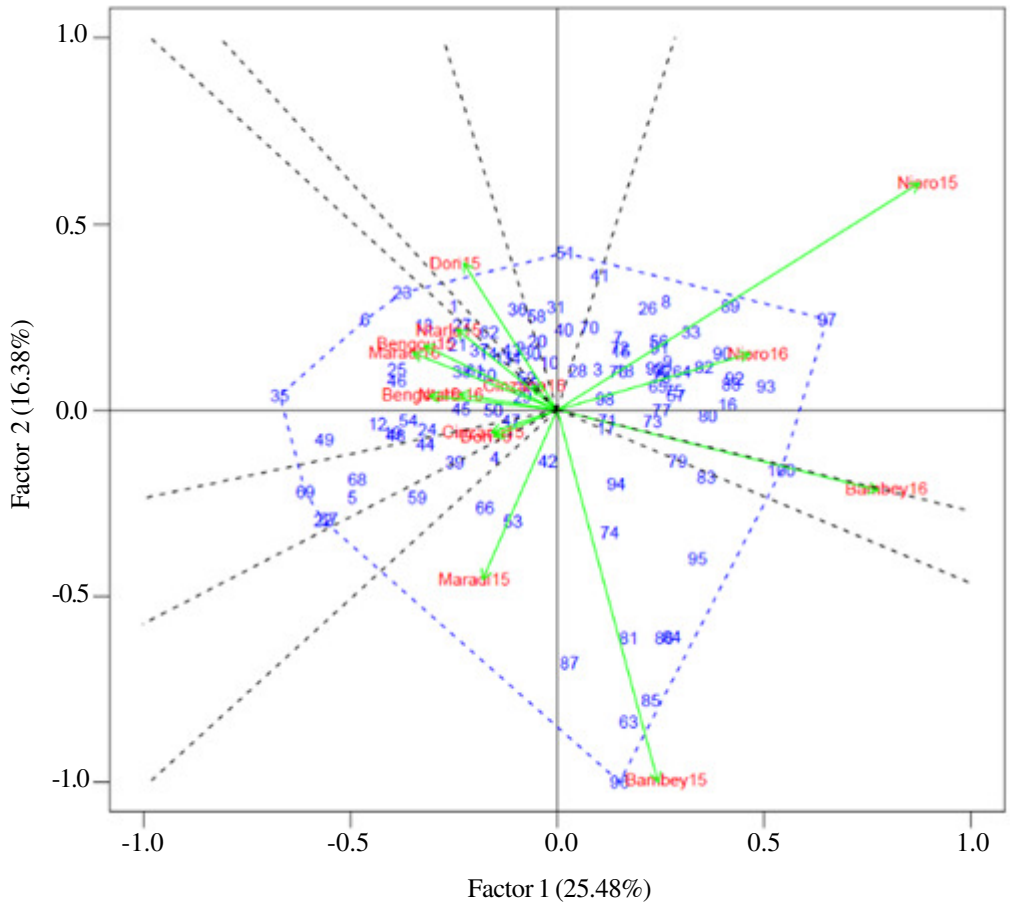


Figure 2. Principal components of the genotypes and environments. Factor 1 (PC1), 2 (PC2), and 3 (PC2) explained 25.48, 16.38, 13.24% of the total variation, respectively. The environment names are location names and year combinations.

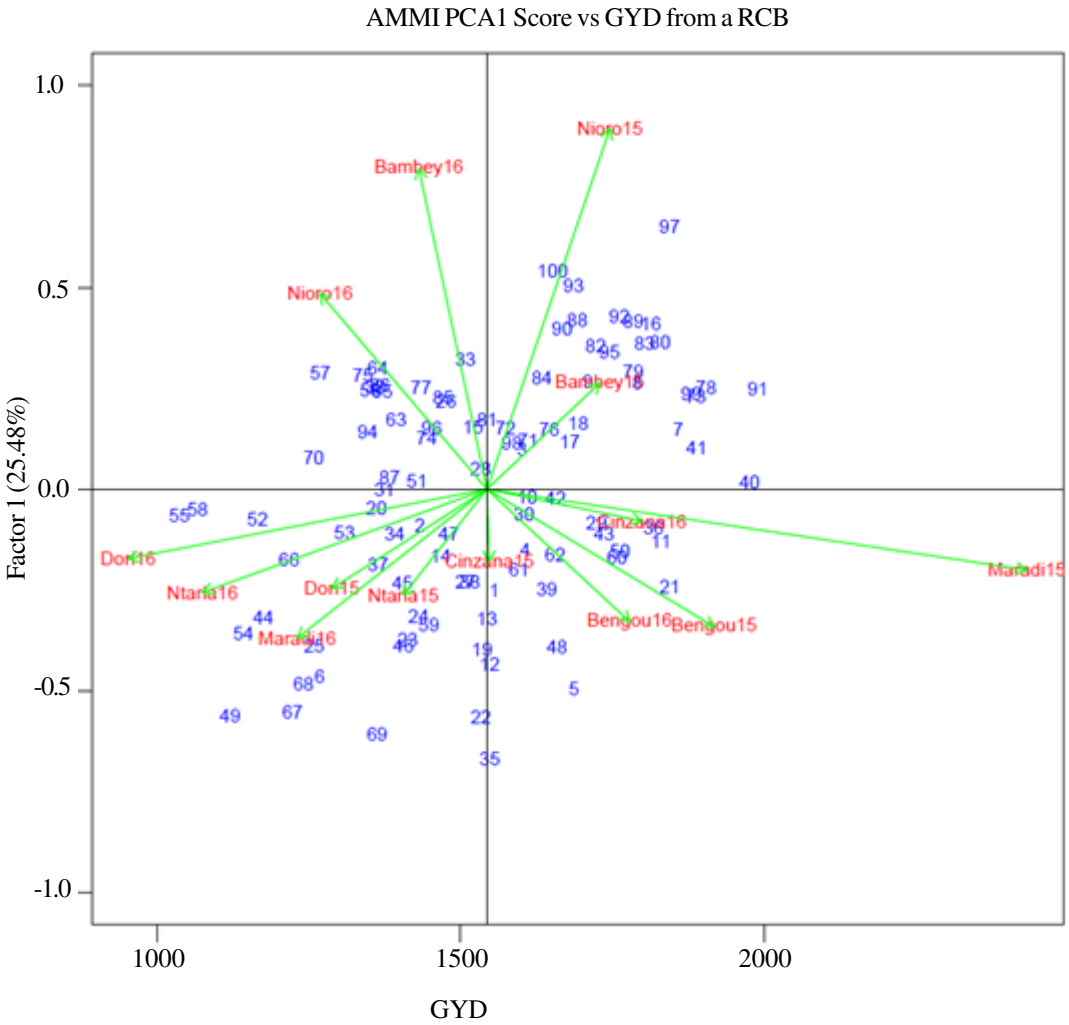


Figure 3. AMMI biplot illustrating the mean grain yield (kg ha^{-1}) (main effect) vs. stability (IPC1 or factor 1) view of both genotypes (blue) and environments (red) for 100 genotypes evaluated at a total of 14 environments during 2015 and 2016 growing seasons. Environments names are as given in Figure 2.

were located at the vertices of the polygon. To the contrary, genotypes 49 (SMILML15), 52 (SMILML18), 55 (SMILNG1) and 58 (SMILNG4) showed the least overall mean grain yield performance. Genotypes distributed around the centre of the graph such as 3 (SMILBF3), 10 (SMILBF10), 14 (SMILBF14), 39 (SMILML5), 76 (SMILNG22) and 94 (SMILSG17) had more stable grain yield performance than the others.

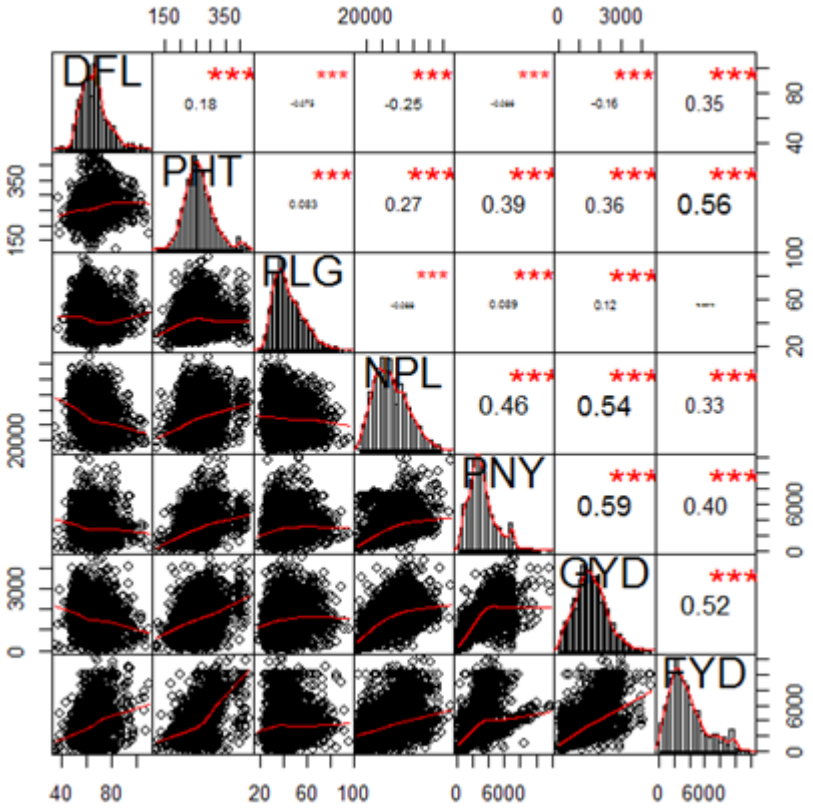
In the present study, Sahelian (Dori, Burkina Faso; Maradi, Niger; N'tarla, Mali; and Bambey, Senegal) and Sudanian (Cinzana, Mali and Bengou, Niger), as well as the locations described as Sudano-Sahelian (Nioro, Senegal) were included. Data analysis indicated that Maradi15, Nioro15, Bambey15, Cinzana16, Bengou15, and Bengou16 were categorised as high yielding environments.

Although different parameters are used by the two models, almost similar results were obtained. The two stability systems confirmed that genotypes 10 (SMILBF10), 14 (SMILBF14), 39 (SMILML5), 76

(SMILNG22) and 94 (SMILSG17) are widely adaptable and should be considered for region wide variety release.

Yield stability usually refers to a genotype's ability to perform consistently across a wide range of spatial or temporal variations in agroclimatic conditions (Eberhart and Russell, 1966). Prevalence of genotype-by-environment interaction (GEI) has a negative impact on the selection of crop cultivars based on overall mean performance per se. Therefore, analysis of stability of performance of a new genotype in a given set of environments is paramount to select a widely adaptable or a specifically adapted cultivar of a crop (Yan and Hunt, 2010).

Correlations among traits. The correlation coefficients among yield and contributing morphological and phenological traits showed that PNY, NPL, PLG and PHT were significantly and positively correlated with grain and fodder yields (Fig. 4). PNY (r = 0.59) and NPL (r = 0.54) were the two most important GYD contributing factors. PHT and DFL showed significantly positive correlation with the fodder yield (r = 0.56 and r = 0.35, respectively). PHT also had significant positive



, * Significant at P < 0.01 and P < 0.001, respectively

Figure 4. Scatter plots, frequency distributions, and relationships among the studied traits for 100 dual-purpose pearl millet accessions evaluated at a total of 14 environments during 2015 and 2016 in Burkina Faso, Mali, Niger, and Senegal. DFL = Days to 50% flowering; PHT = Plant height (cm); PLG = Panicle length (cm); NPL = Number of panicles per hectare; PNY = Panicle yield (kg ha^{-1}); GYD = Grain yield (kg ha^{-1}); and FYD = Fodder yield (kg ha^{-1}).

correlation with GYD (r = 0.36). On the other hand, DFL had negative correlation (r = -0.16) with grain yield implying that extremely late maturing genotypes are not preferred.

The correlation coefficients among the component traits indicated a general tendency that tall plants flowered later than the shorter accessions, but were not strongly correlated. On the other hand, tall plants had the advantage of increasing both grain and fodder yields. As the coefficient of correlation measures the strength and direction of a relationship between two traits (Sella and Barton, 2019), it is very important for effective indirect selection of complex traits like yield using simply measurable proxy traits such as PHT and NPL. Therefore, DFL, NPL, PNY, and PHT are important selection targets to improve both grain and fodder yields. In the evaluation for dual-purpose pearl millet, late flowering, tall plant height and panicle size and number are better be considered important characteristics for selection.

The two economically important traits, GYD and FYD were highly significantly and positively correlated (Fig. 4). This suggests that concomitant improvement for pearl millet fodder yield can be achieved through selection for tall genotypes from the landraces, without compromising grain yield. Based on overall mean grain and fodder yields, genotypes such as SMILML2, SMILML6, SMILBF11, SMILBF21, SMILSG20, and SMILSG22 presented outstanding performance. Therefore, these genotypes need to be further evaluated for release as a dual-purpose cultivar in the region.

In this study, PHT, PNY and PLG were most important traits for maximising grain and fodder yields because of their high significant positive correlation coefficients (Fig. 4). Previous studies also reported positive correlations of productive tillers, panicle length, panicle girth, days to maturity to grain yield in pearl millet (Govindaraj *et al.,* 2013; Sattler *et al.,* 2018). Similarly, genotypes with tall height, high panicle weight and panicle harvest index were indicated to likely increase grain yield in sorghum (Da Silva *et al*., 2017). Although DFL was positively correlated with FYD, its correlation with grain yield was negative, implying very late flowering genotypes are not preferred in breeding for dual-purpose millet varieties.

CONCLUSION

The two years evaluation of selected accessions from the breeding programmes in the West African region indicates the prevalence of ample germplasm resources for breeding dual-purpose pearl millet in the region. The result of the study showed a variation among the accessions tested, environments and GEI. Stability analysis using Eberhart and Russell as well as AMMI approaches identified several generally adaptable genotypes. Accordingly, SMILBF10 and SMILBF14 from Burkina Faso, SMILML5 from Mali, SMILNG22 from Niger, and SMILSG17 from Senegal had overall better performance. In general, population hybrids and composite varieties performed better than the open pollinated varieties across the environments. Regionally integrated breeding programmes with effective germplasm exchange and information sharing will have significant leveraging effect in developing desirable pearl millet cultivars in the region.

The significant positive correlation of grain and fodder yields with the major contributing traits such as PHT, PNL, and PNY can be leveraged in simultaneous indirect selection for high yielding dual-purpose cultivars.

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