

Graphical Analysis of Genotype × Environment Interaction and Stability of Grain Yield in Maize. The search for an ideal genotype

Adeniji, O.T¹., Badmus A.A¹., Jandong, E²., Owoseni, A¹., Olorunwo, T¹., Adekoya, M.A³., and Olutayo, G¹.

¹Department of Crop Science and Horticulture, Federal University Oye Ekiti, Nigeria

²Department of Crop Science and Horticulture, Taraba State University, Jalingo, Nigeria

³Department of Plant Science and Biotechnology, Federal University Oye Ekiti, Nigeria

Author for correspondence: waleniji@gmail.com, olawale.adeniji@fuoye.edu.ng

Abstract

The interactions between genotype and environment (GEI) and their stability concerning grain yield (GY), grain dry matter (GDM), and stover dry matter (VDM) yield were examined among eight genotypes across eight environments (seven in Ekiti State and one in Taraba State). The objective of the study was to identify promising maize genotypes suitable for both specific and broad adaptation, as well as to select the most favourable environments. A randomized complete block design with three replicates was employed to allocate genotypes to experimental units, utilizing a plant-to-plant spacing of 0.50 m and a row-to-row distance of 0.75 m. Calculations were made for GY, GDM, and VDM. An analysis of variance was conducted for each year, along with a combined analysis over years using the PROC GLM procedure of SAS version 9.2. The effects of GEI were evaluated using GEA-R (Version 4.1). A GE biplot was constructed based on Column Metric Preserving, tester-centered methodology, without scaling. Significant mean squares were detected for genotype, environment, and replication concerning GY, GDM, and VDM. The analysis revealed significant mean squares ($P \leq 0.05$) for GY, GDM, and VDM due to GEI. DMR-LSR-Y outperformed all other genotypes for GY, while it, along with SWAN-1-SR-Y and LNTP-Y, excelled in GDM. The top performers for VDM included OBA SUPER-6, DMR-LSR-Y, and BR-9928-DMR-SR-Y. Aiyetoro shows promise for identifying superior genotypes across GY, GDM, and VDM. The study recommends the inclusion of DMR-LSR-Y and LNTP-Y in multi-location testing in preparation for variety release, with DMR-LSR-Y identified as the ideal cultivar for VDM. Additionally, hybridization between DMR-LSR-Y and LNTP-Y may facilitate the development of segregating populations with improved GY, GDM, and VDM.

Keywords: Maize genotypes, grain yield, grain dry matter yield, stover dry matter yield, cross-over performance, multiple environments.

Introduction

Maize is a high-value cereal crop of significant economic importance for domestic consumption and industrial growth. Maize is cultivated in mixtures with root and stem tuber crops and legumes under rain-fed conditions in small household plots and large-scale farms (FMARD, 2022) across the humid rainforest, guinea, and Sudan savannah agro-ecologies in sub-Saharan Africa. The grain yield of 6.53 Kg ha⁻¹ was harvested in China in 2023 (Statistica, 2023), which is larger than the world average of 5.75 kg ha⁻¹ for 2021 (FAOSTAT, 2020). In Nigeria, maize production increased from 639,000 tonnes to 12.7 million tonnes between 1972 and 2021, with an average annual growth rate of 9.37%. This was due to the increase in land area under cultivation and not access to high-yielding, nutrient-dense, and disease-resistant hybrid or open-pollinated varieties. The maize grains and stover are reliable sources of high protein and energy, fiber, and sugar for humans and livestock, bio-fertilizers and biogas, and raw materials for industries.

In addition, maize grain and stover yields are closely related to dry matter accumulation, which is predicated on soil nutrition, crop rotation, weed management, and the split application of fertilizers. In the tropics, maize yield is impacted negatively by high humidity, inconsistent and inadequate precipitation in time and space, heat stress prolonged dry season and flooding (Dao et al. 2015) and losses in grain yield due to biotic (attacks by streak virus, bacterial blight and common rust) and abiotic stressors over time drive the emergence of biotic and abiotic stresses and further exacerbate maize productivity. Food insecurity can be mitigated by increasing crop yield per unit area of land without compromising the environment. The concern among plant breeders is the desire to develop phenotypically stable genotypes for diverse production environments defined by agro-climatic factors, managing genotype × environment interaction (GEI), and identifying environments promising for specific maize products.

The crop improvement plan requires continuous evaluation of maize genotypes (open-pollinated, hybrid, and breeding lines) in multiple environments to pick superior genotypes for grain yield with adaptation to broad and specific environments for cultivar development (Djurovic et al. 2014; Zewdu *et al.*, 2020) under changing biotic and abiotic

factors. (Zewdu *et al.* 2020). The stratification of the crop-growing environment enhances the identification and selection of productive genotypes, eliminates redundant loci, reduces experimental costs, and increases efficiency (Zewdu *et al.* 2020). GEI minimizes the correlation between genotypic and phenotypic expression, resulting in a decrease in genetic gain after the selection of traits of economic importance. On the other hand, GEI enables the identification of genotypes with static or dynamic stability adapted to varying environments. The standard analysis of variance does not account for non-additive terms but assumes homogeneity (Mitrovic *et al.* 2012). The genotype, and genotype \times environment interaction (GGE) is a throughput statistical tool, a linear-bilinear model that does not take into account the main effect associated with the environment for multi-environment experimental data sets. The GGE model explains adaptability and stability analyses for both specific and broad adaptations to environments, and identifies factors responsible for differences in environmental conditions (Tena *et al.* 2019). The GGE biplot identifies genotype-discriminating environments to enhance selection efficiency and select genotypes adapted to specific environments.

In maize-growing agro-ecologies, improved maize varieties have the potential to increase grain yield and productivity. On the other hand, commercial hybrids and open-pollinated varieties have shown declining grain yields primarily due to biotic and abiotic stresses, as well as changes in weather patterns from one environment to another. Industries have shown an increasing demand not only for grain yield but also for grain dry matter yield and stover dry matter yield. In Nigeria, differential performance among cultivated varieties for grain yield and yield components is associated with changes in temperature and precipitation, altitude, and radiation, which are primary factors influencing post-silking dry matter and grain yield.

In sub-Saharan Africa, there is a dearth of knowledge in agronomic performance, stability, and genetic components for grain yield, grain dry matter, and stover dry matter yield among commercially grown maize varieties across maize growing agro-ecologies in the rain forest, derived savannah and guinea savannah. In addition, many commercial varieties grown by farmers are aging with declining grain yield, and consequently, a shortfall in domestic grain supply for industries. Therefore, it is imperative to identify promising environments and genotypes for grain yield, grain dry matter yield, and stover dry matter yield, and select promising breeding lines to replace poor-performing and old commercial varieties. This study was undertaken to quantify the magnitude of variation among maize genotypes for grain yield, grain dry matter, stover dry matter yield across contrasting environments, and select promising maize genotypes for specific and broad adaptation across environments. Additionally, to identify the best environment for grain yield, grain and stover dry matter yield.

Materials and Methods

Experimental sites

The research environments are situated in the rainforest agroecology, the derived guinea savannah agroecology, and the guinea savannah agroecology (Table 1). The meteorological data (average annual precipitation, relative humidity, mean daily temperature, and solar radiation) for each environment during 2020 and 2021 were retrieved from the US NASA/POWER CARES/MERRA2 DAILY DATA (Aqua Crop software, 2021).

Physical and chemical properties of the soil

Before land preparation, five soil samples were collected from 0 – 30 cm depth from each location. Thereafter, a composite sample was analyzed for soil physical properties, soil pH (1:2.5 in water), electrical conductivity (1:2.5 in water), texture using the hydrometer method, organic carbon; total nitrogen using Kjeldahl method, phosphorus using Bray 1 method, potassium, calcium and magnesium with quantification in an atomic absorption spectrometer (Day, 1965; Nelson and Sommers, 1996; Wilke, 2005; Bray and Kurtz, 1945).

Germplasm, Field Planting, and Crop Husbandry

Maize genotypes, viz. [G1 (SWAN 1 SR-Y), G2 ('BR-9928-DMR-SR-Y'), G3 ('OBA SUPER 2'), G4 ('DMR-LSR-Y'), G5 ('DMR-ESR-Y'), G6 ('LNT-P-Y'), G7 ('OBA SUPER 6') and (G8) 'FARMER'S VARIETY' (Check)] used in this experiment were recommended by the Institute of Agricultural Research and Training, Ibadan and Ekiti State Agricultural Development Project, Nigeria. The field was manually cleared using handheld cutlasses, ploughed, harrowed, and levelled. A randomized complete block design (RCBD) with three replications was employed to allocate the genotypes to the experimental units. A plot comprised of five rows of 12 meters long and 0.75 m between rows, and each replicate was separated by a 1.5 m distance. Field planting took place on 30th April and 3rd May 2020 and 2021, respectively. At planting, two grains are planted per hole at a spacing of 0.50 m plant-to-plant distance and row-to-row distance of 0.75 m. Thinning was done one week after planting (WAP). The experiments were maintained weed-free manually. At two WAP, 10 g of insecticide Caterpillar force® (a.i. Emamectin Benzoate 5 % WDG Corporations S.A, Switzerland) was dissolved in 15 l of water to control fall armyworm (FAW). At three WAP, a compound mineral fertilizer (N20: P10: K10) was applied at 200 kg/ha (40 kg N, 20 kg P2O5, and 20 kg K2O), followed by Urea (46 kg N/ha) fertilizer at 100kg/ha at 6 WAP.

Data collection and statistical computation

After culling, the ears were dried, shelled, and weighed to determine grain weight. The Dickey–John moisture meter, Mini GAC® 2500, United States, was used to determine the moisture content in the grains. The GY/plot, GDM, and VDM were calculated according to the formula designed by Dobermann (2005). The variance homogeneity test of error variance showed an insignificant response. Thereafter, the analysis of variance was performed for each year and combined for 2020 and 2021 using the PROC GLM procedure of SAS 9.2 version, SAS Institute., Cary, NC SAS (2012). The means were separated by using the Tukey HSD test. The genotype was a fixed factor while the year and environment were random factors. With significant GEI, stability analysis was applied. The $G \times E$ interaction effect on GY, GDM, and VDM was calculated using GEA-R (Version 4.1). The principal component analysis (PCA) was done in META-R. Due to a statistically significant Genotype \times Year Interaction, Years \times Environments Interaction was regarded as environment. The $G, G \times E$ biplot was drawn based on Column Metric Preserving, tester-centered with no scaling (Yan and Tinker, 2006). Where E1 to E19 were environments and G1-G8 = maize genotypes.

Table 1. Environments, geographic position, and agroecological zones for the eighteen environments in Nigeria.

Environment	Environment code	Longitude and Latitude (asl)	Altitude (m)	Agro ecological classification
Ikole-Ekiti, Nigeria	E1, E10	Longitude: 5.49 (5° 29' E) Latitude: 7.80 (7°48'N)	535.5 m	Derived Guinea savannah agro ecological zone
Are village, Ikole, Nigeria	E2, E11	Longitude: 5.10 (5° 30' E) Latitude: 7.77 (7°46'N)	570.5 m	Derived Guinea savannah agro ecological zone
Ado-Odo village, Ido/Osi, Nigeria	E3, E12	Longitude: 5.27 (5° 16' E) Latitude: 7.83 (7°49'N)	476.7 m	Rain forest agro ecological zone
Ayetoro village, Ilumoba, Nigeria	E4, E13	Longitude: 5.43 (5° 25' E) Latitude: 7.63 (7°38'N)	377.6 m	Rain forest agro ecology
Osun kurudu village, Nigeria	E5, E14	Longitude: 5.26 (5° 15' E) Latitude: 7.75 (7° 5'N)	341.2 m	Rain forest guinea savannah
Isaboro village, Nigeria	E6, E15	Longitude : 5.20 (5° 12' E) Latitude: 7.85 (7°51'N)	633.2 m	Northern guinea savannah agro ecological zone
Ijesa-modu village, Nigeria	E7, E16	Longitude : 5.23 (5° 14' E) Latitude: 7.96 (7°57'N)	551.7 m	Northern guinea savannah agro ecological zone
Ogbese village, Nigeria	E8, E17	Longitude : 5.30 (5° 18' E) Latitude: 7.44 (7°26'N)	342.4 m	The rainforest agro ecological zone
Jalingo, Nigeria	E9, E18	Longitude: 11°22'E Latitude: 08.52°46'N	222 m	Guinea savannah agro ecological zone

E1 to E9= 2020 evaluation; E9 to E18= 2021 evaluation.

Results

Physical and chemical properties of the soils

The soil samples from E3, E13 (Ado-Odo) showed high organic matter content, next were (E6, E15) Isaboro village, (Table 2) soil samples from E4 and E13 (Ayetoro) had low OM, but low OM in E4, E13 (Ayetoro village). The P (%) content was generally low in all locations except E3, E12 (Ado-Odo village), Total nitrogen (%), potassium, and Exchangeable Cation Exchange Capacity were high in E3, E12 (Ado-Odo village). The available potassium in the soil was highest in E5, E14 (Osun-Kuduru village), and E3, E12 (Ado-Odo village). While the soil pH was near neutral at all locations. The soil textural class was loamy sand in all locations except Ayetoro village, which is predominantly sandy soil.

Grain Yield, Grain Dry Matter Yield, and Stover Dry Matter Yield among the maize genotypes across environments and years

Table 3 depicts the F-test (p values) of the genotypes evaluated in 18 environments across 2020 and 2021. The mean squares for genotype (G), environments (location and years), and replications (Environment \times Years), showed statistically significant ($P \leq 0.05$) mean squares for grain yield, grain dry matter and stover dry matter (Table 3). The second-order interaction, the GEI, revealed statistically significant ($P \leq 0.05$) mean squares for grain yield, grain dry matter and stover dry matter. The maize genotypes recorded variable performance due to differences in the micro and macro environmental factors and soil physico-chemical properties. Coefficients of variability (CV%) was 5.29 % in stover dry matter, grain yield (6.64 %), and stover dry matter yield (6.82 %). Five genotypes, viz. 'DMR-LSR-Y', 'DMR-ESR-Y', 'OBA SUPER 6', SWAN 1 SR-Y, and 'BR-9928-DMR-SR-Y' had mean values for grain yield above the population mean (3.45 kg). The mean value for grain yield was low (2.28 Kg) in the 'FARMER'S VARIETY' to moderate (4.04 Kg) in 'DMR-LSR-Y' (Table 4). The top three genotypes for grain yield across the 18 environments were 'DMR-LSR-Y' (3.99 Kg), 'LNTP-Y' (3.96 Kg), and 'OBA SUPER 6' (3.83 Kg). The genotype 'DMR-LSR-Y' outyielded the commercial varieties, breeding lines, and the check for grain yield. Across the 18 environments, 'DMR-LSR-Y', SWAN 1 SR-Y, and 'LNTP-Y' performed better than other genotypes for grain dry matter yield, while 'OBA SUPER 6', 'DMR-LSR-Y', and 'BR-9928-DMR-SR-Y' performed best for stover dry matter.

Grain Yield

Discriminateness, ranking environments and genotypes for grain yield

The Genotype, Genotype \times Environment interaction biplot showed the discriminateness, representativeness, and ranking of eight (8) maize genotypes and the 18 environments based on GY data (Figures 1a, b, and c). The GGE biplot explained 87.22 % (70.96 % for the first PC and 16.26 % for PC 2) of the total variation. The length of the average tester vector represents the importance of the tester \times environment interaction. E18 and E9 align on the same vector length. E9, E18, E4, E11, E1, E10 and E7 had long vector, E14, E15, E13, E8 and E16 had moderate amplitudes while E3, E12, E5 and E17 had short amplitude from the biplot origin. In the GGE biplot, an arrow pointing to the average tester is the average tester coordinate. The small circle on the average tester coordinate represents an average environment. E13 is located in the concentric ring, next is E8 (Figure 1b). Maize genotypes were ordered into four quadrants, while the eighteen environments were dispersed among quadrants 3 and 4. The representativeness of the test environments was determined by the degree of angle measured between the test environments and the average environment coordinate. The cosine angle between two vectors approximates the correlation coefficient between the two environments. E10 and E17, E2 and E11, and E4 and E16 had angles less than 90° implying positive correlation coefficients between any two genotypes. E16 and E6, E17 and E18, E2 and E14, E7 and E16 had larger angles closer to 180° with the average environment axis meaning a negative correlation between the genotypes. The ranking of the maize genotypes (Figure 1b) showed that 'DMR-LSR-Y' was positioned close to the epicenter of the concentric rings on the AEC. 'LNTP-Y' and 'FARMER'S VARIETY' were located furthest from the center of the concentric rings. E13 lies on the circular ring and E5 on the average environment coordinate. 'DMR-LSR-Y' and 'OBA SUPER 6' were dispersed at the center of the concentric rings, and next were 'BR-9928-DMR-SR-Y' and 'OBA SUPER 2' (Figure 1c).

Mean - stability for grain yield

The maize genotypes were dispersed with greater variability in each direction on the average environment axis. SWAN 1 SR-Y, 'BR-9928-DMR-SR-Y', 'DMR-LSR-Y' and 'OBA SUPER 6' and 'LNTP-Y', 'OBA SUPER 2', 'DMR-ESR-Y', and 'FARMER'S VARIETY' were located above and below the average environment axis with high and low grain yield, respectively (Figure 1d). The direction of the average environment axis is from the low (2.88 g) to the high (3.99 kg) for GY. 'LNTP-Y' had the long projections from the average environment axis followed by SWAN 1 SR-Y, 'BR-9928-DMR-SR-Y', and 'DMR-ESR-Y'. 'OBA SUPER 2' lies on the AEC with moderately high (3.43 Kg) GY and minimal projection from the AEC. GY was highest (3.99 Kg) in 'DMR-LSR-Y', 'OBA SUPER 6' (3.83 Kg), while 'FARMER'S VARIETY' (2.28 Kg) recorded the lowest grain yield. The distance between two entries and the center of the concentric ring represents stability and yield potential. 'DMR-LSR-Y', 'OBA SUPER 6', and 'FARMER'S VARIETY' had moderate projections from the average environment coordinate. Environments 18 and E9 were ordinated with the highest variability, while E13 was dispersed in the hypothetical average environment coordinate, and E8 was closest to E13 with the least variability.

Table 2. Physical and chemical properties of the soils from 0 – 30 cm in each environment during 2020 and 2021.

Sample Name	Soil particle size analyses (g ⁻¹ kg)				Elemental composition										
	Sand (g/kg)	Silt (g/kg)	Clay (g/kg)	Texture	pH in Water	Organic Matter (%)	Total Nitrogen (%)	Avail P (mg/Kg)	K (cMol/kg)	Na (cMol/kg)	Ca (cMol/kg)	Mg (cMol/kg)	ECEC (cMol/kg)	Exh Acidity (cMol/kg)	
E1, E10	838.40	99.2	62.4	Loamy sand	5.5	1.71	0.11	5.09	0.11	0.04	1.03	0.19	2.16	0.8	
E2, E11	798.40	149.2	52.4	Loamy sand	6.8	1.68	0.10	6.63	0.12	0.04	0.98	0.20	2.26	0.92	
E3, E12	778.40	149.2	72.4	Loamy sand	6.3	3.81	0.18	4.61	0.26	0.04	2.98	0.26	4.38	0.84	
E4, E13	868.40	79.2	52.4	Loamy sand	5.8	2.92	0.15	3.67	0.10	0.04	1.74	0.26	2.93	0.8	
E5, E14	878.40	69.2	52.4	Sand	7.1	1.44	0.10	6.70	0.14	0.04	1.52	0.24	2.55	0.6	
E6, E15	818.4	119.2	62.4	Loamy sand	7.1	3.87	0.15	5.65	0.12	0.04	7.30	0.29	8.59	0.84	
E7, E16	798.40	149.2	52.4	Loamy sand	6.8	3.74	0.18	3.91	0.20	0.04	3.77	0.30	5.09	0.78	
E8, E17	798.40	139.2	62.4	Loamy sand	7.9	4.46	0.20	9.48	0.26	0.04	9.43	0.32	10.99	0.94	
E9, E18	778.40	159.2	62.4	Loamy sand	7.9	3.77	0.13	10.09	0.08	0.04	1.90	0.14	2.84	0.68	

Table 3. Mean squares for grain yield (GY), grain dry matter (GDM), and stover dry matter (VDM) of 8 maize genotype evaluated in 18 environments in Nigeria during 2020 and 2021.

Source of variation	Degree of freedom	Grain yield (kg/plot)	Grain dry matter yield (kg/plot)	Stover dry matter yield (kg/plot)
Year	1	7.25**	41.39**	42.86**
Environment	17	5.90**	72.58**	149.18**
Replication (Environment × Year)	36	0.07*	0.22**	458.97**
Genotypes	7	17.71**	69.05**	458.77**
Genotype × Environment	119	0.58**	4.22**	23.06**
Error	252	0.05	0.26	0.51
Mean		3.45	7.54	13.46
CV (%)		6.64	6.82	5.29

Table 4. Least square mean for Grain yield, grain dry matter, and stover yield among eight maize genotypes across 18 environments in Nigeria in 2020 and 2021.

Genotypes	Grain Yield Kg/plot	Rank	Grain Matter (Kg/plot)	Dry Rank	Stover Matter (Kg/plot)	Dry Rank
‘SUWAN 1 SR-Y’	3.58c		8.43a	2	11.17e	
‘BR-9928-DMR-SR-Y’	3.55c		7.76c		12.73d	
‘OBA SUPER 2’	3.43d		7.79c		15.19c	3
‘DMR-LSR-Y’	3.99a	1	8.51a	1	14.95c	
‘DMR-ESR-W’	2.98e		6.19d		10.95e	
‘LNTTP-Y’	3.96a	2	8.18b	3	16.52b	2
‘OBA SUPER 6’	3.83b	3	8.04b		17.11a	1
‘FARMER’S VARIETY’	2.28f		5.39e		9.04f	

Table 5. Mean values and rank for GY, GDM, and VDM in 18 environments during 2020 and 2021 and pooled.

Grain yield							
Environment	Year 1	Rank	Environment	Year 2	Rank	Pooled Mean	Rank
E1	4.01a	1	E10	3.98	2	4.00	2
E2	3.25b		E11	3.79a		3.52	
E3	2.66b		E12	2.77		2.72	
E4	3.29b		E13	2.50		1.93	
E5	2.62b		E14	3.04		2.83	
E6	3.58ab	2	E15	3.93		3.76	3
E7	3.06b		E16	3.26		3.16	
E8	3.35b		E17	3.98	2	3.67	
E9	4.09a	1	E18	4.06	1	4.08	1
Grain dry matter							
E1	9.42	3	E10	9.39	2	9.41	2
E2	9.39a	2	E11	8.65b		9.02	2
E3	5.52b		E12	6.52a		6.02	
E4	8.44b		E13	8.74a		8.59	
E5	5.54b		E14	6.46a		6.00	
E6	6.39b		E15	6.89a		6.64	
E7	5.20a		E16	4.87b		5.04	
E8	6.08b		E17	8.77a	3	7.43	
E9	9.84a	1	E18	9.57a	1	9.71	1
Stover dry matter							
E1	12.84		E10	18.17	1	15.51	1
E2	8.51		E11	16.86	2	12.69	
E3	12.89		E12	14.75		13.32	
E4	10.80		E13	13.56		12.18	
E5	12.34		E14	12.83		12.59	
E6	15.80	1	E15	11.78		13.79	
E7	16.34		E16	11.35		13.85	3
E8	14.07	3	E17	10.75		12.41	
E9	15.27	2	E18	14.75	3	15.01	2

Which won where/what for grain yield

The which - won - where for grain yield visualizes the interaction between the 18 environments and the performance of eight genotypes for grain yield (Figure 1d). The vectors revealed the genotypes that outperformed others in each environment. The polygon had four sectors, and the 18 environments were dispersed into three sectors on the GGE plot (Figure 1e). The cluster of environments contained in each of the three sectors is called the mega-environment. Entries ordinated in the vertices were SWAN 1 SR-Y, ‘DMR-LSR-Y’, ‘LNTP-Y’, and ‘FARMER’S VARIETY’. The vertex genotypes had the highest grain yield in each mega-environment. ‘OBA SUPER 6’, ‘BR-9928-DMR-SR-Y’, ‘OBA SUPER 2’, and ‘DMR-ESR-Y’ were dispersed within the polygon. SWAN 1 SR-Y recorded the highest mean value (3.58 Kg) for grain yield and was most adapted to the first mega-environment, which comprised E7, E16, E14, E3, and E12. ‘DMR-LSR-Y’ recorded highest grain yield (3.99 Kg) in the second mega-environment (E1, E15 and E8) while ‘LNTP-Y’ with 3.96 Kg/plot is the vertex genotype in the third mega-environment (E4, E10, E13, E5, E17, E4, E11, E2, E6, E9 and E18). The ‘FARMER’S VARIETY’ is the vertex genotype in the fourth mega-environment with the least grain yield (2.28 Kg/plot), and no environment was ordinated in the fourth mega-environment.

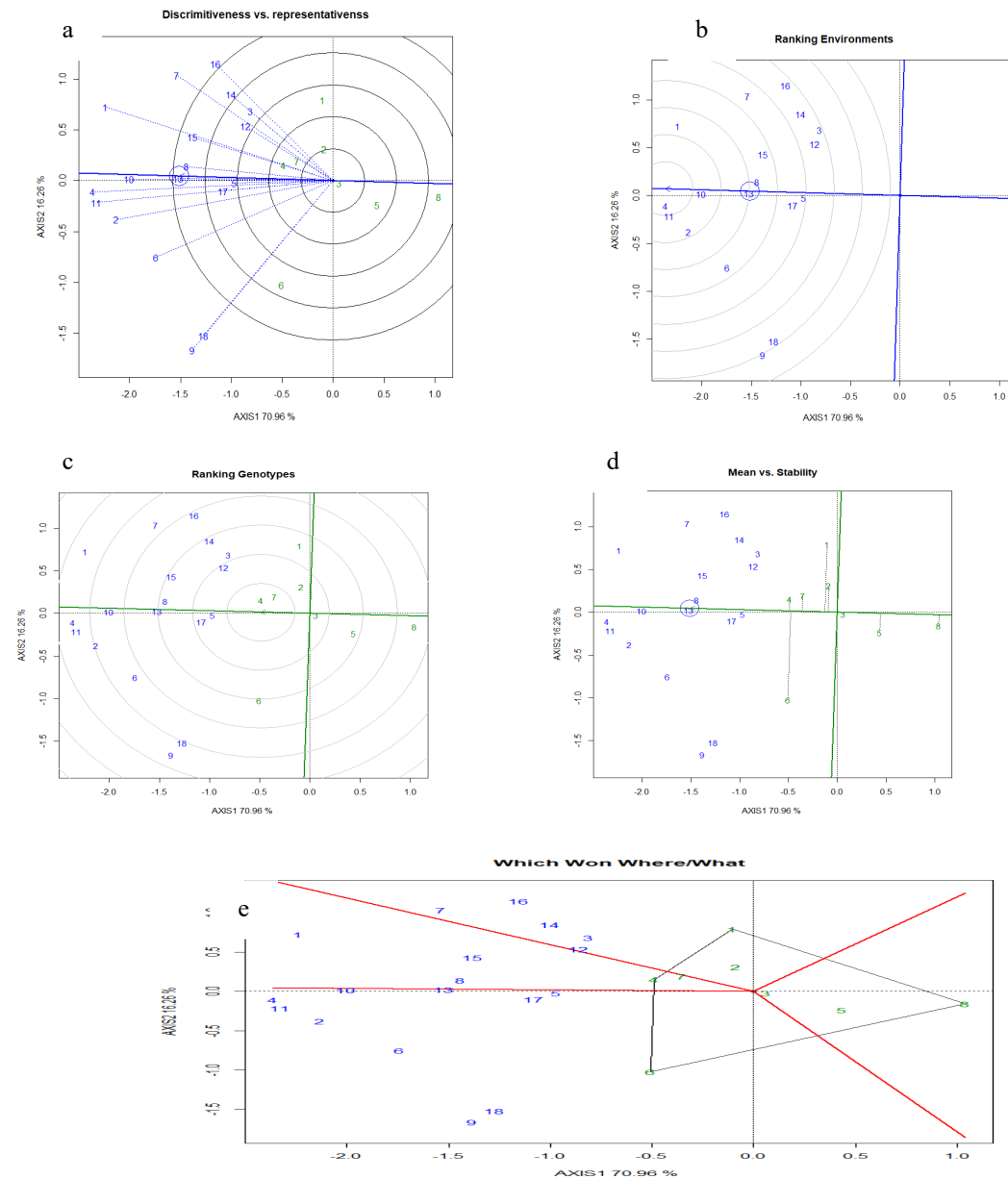


Figure 1a-e. Discriminateness vs representativeness (a), ranking environment (b), ranking genotypes (c), means vs. stability (d) and which won where/what (e) and Maize genotypes G1 (SWAN 1 SR-Y), G2 ('BR-9928-DMR-SR-Y'), G3 ('OBA SUPER 2'), G4 ('DMR-LSR-Y'), G5 ('DMR-ESR-Y'), G6 ('LNTP-Y'), G7 ('OBA SUPER 6') and "FARMER'S VARIETY" (G8),

Discriminateness, ranking environments, and genotypes for stover dry matter yield

The GGE biplot for stover dry matter yield showed PC axis 1 to have contributed 68.54 %, altogether with PC axis 2, giving a cumulative of 80.18 % (Figure 2a). The eight genotypes were dispersed into the four quadrants, while the 18 environments were ordinated into Q1 and Q4. The biplot for stover dry matter yield showed the interrelationships among the 18 tested environments. The environmental vectors for maize stover dry matter yield are the line drawn from the biplot origin. The angle between the vectors of two environments represents the association between the two environments. E15 had the longest vector length while E4 had the shortest vector length (Figure 2a). The cosine angle between E7 and E15, E8 and E6, E17, and E6 is obtuse. On the other hand, E5 and E18, E4 and E2, and E4 and E13 had the smallest angles ($< 90^\circ$) between each pair of environments.

Mean vs stability for stover dry matter yield

The GGE biplot (means vs stability) for stover dry matter yield (Figure 2b) showed the direction of average environment axis from low to high mean values for stover dry matter yield. The maize genotypes were ranked according to their projection and direction from the average environment coordinate. SWAN 1 SR-Y (G1), 'BR-9928-DMR-SR-Y', 'OBA SUPER 2', 'OBA SUPER 6' and 'FARMER'S VARIETY' were ordinated below the average environment axis while 'DMR-ESR-Y', 'DMR-LSR-Y' and 'LNTP-Y' were dispersed above the average environment axis. 'OBA SUPER 6' and 'LNTP-Y' had high stover dry matter yield. 'FARMER'S VARIETY' and 'DMR-ESR-Y' performed poorly for stover dry matter yield. The genotypic performance for stover dry matter yield on the average environment coordinate is similar to the mean values for grain dry matter yield for each genotype (Table 2). 'DMR-ESR-Y' had a long amplitude from average environment axis. 'OBA SUPER 6' had the shortest vector from average environment axis. The vector length of SWAN 1 SR-Y is twice the vector length of 'DMR-ESR-Y'. Further, 'OBA SUPER 6' was closest to the average environment coordinate abscissa compared to other genotypes. E15 and E17 were dispersed widely from other environments, representing contrasting environments. E4, E2, E1, E13, and E12 were placed on the average environment axis abscissa, while other environments showed variable performance. The genotypes showed moderate dispersion from average environment axis for stover dry matter yield.

Which won where/what for stover dry matter yield

The polygon showing which won where/what for stover dry matter yield was drawn by connecting data points for the entries further away from the origin; the remainder of the genotypes were dispersed within the polygon (Figure 2b). Eighteen (18) environments were ordinated in two of the six sectors (Figure 2c). Three environments, viz. E6, E8, E17 formed one mega-environment while E4, E11, E7, E18, E16, E9, E3, E13, E1, E14, E2, E5, E10, and E12 constitute the second mega-environment (Figure 2c). Genotypes found at the vertices were 'DMR-ESR-Y', 'LNTP-Y', 'OBA SUPER 6', 'OBA SUPER 2', SWAN 1 SR-Y, and 'FARMER'S VARIETY' with the longest vector length in each sector. 'DMR-LSR-Y' and 'BR-9928-DMR-SR-Y' were dispersed within the polygon. 'DMR-ESR-Y', 'OBA SUPER 2', SWAN 1 SR-Y, and 'FARMER'S VARIETY' performed best for stover dry matter yield in their respective sector with no specific adaptation to any environment. 'OBA SUPER 6' showed proximity to the second mega environment, while 'LNTP-Y' had proximity to E6, E8, and E17. 'DMR-ESR-Y' had the longest vector to the biplot origin in their respective direction. 'DMR-LSR-Y' and 'BR-9928-DMR-SR-Y' were located within the polygon. 'DMR-ESR-Y' is superior for stover dry matter yield while 'LNTP-Y' and 'FARMER'S VARIETY' are inferior.

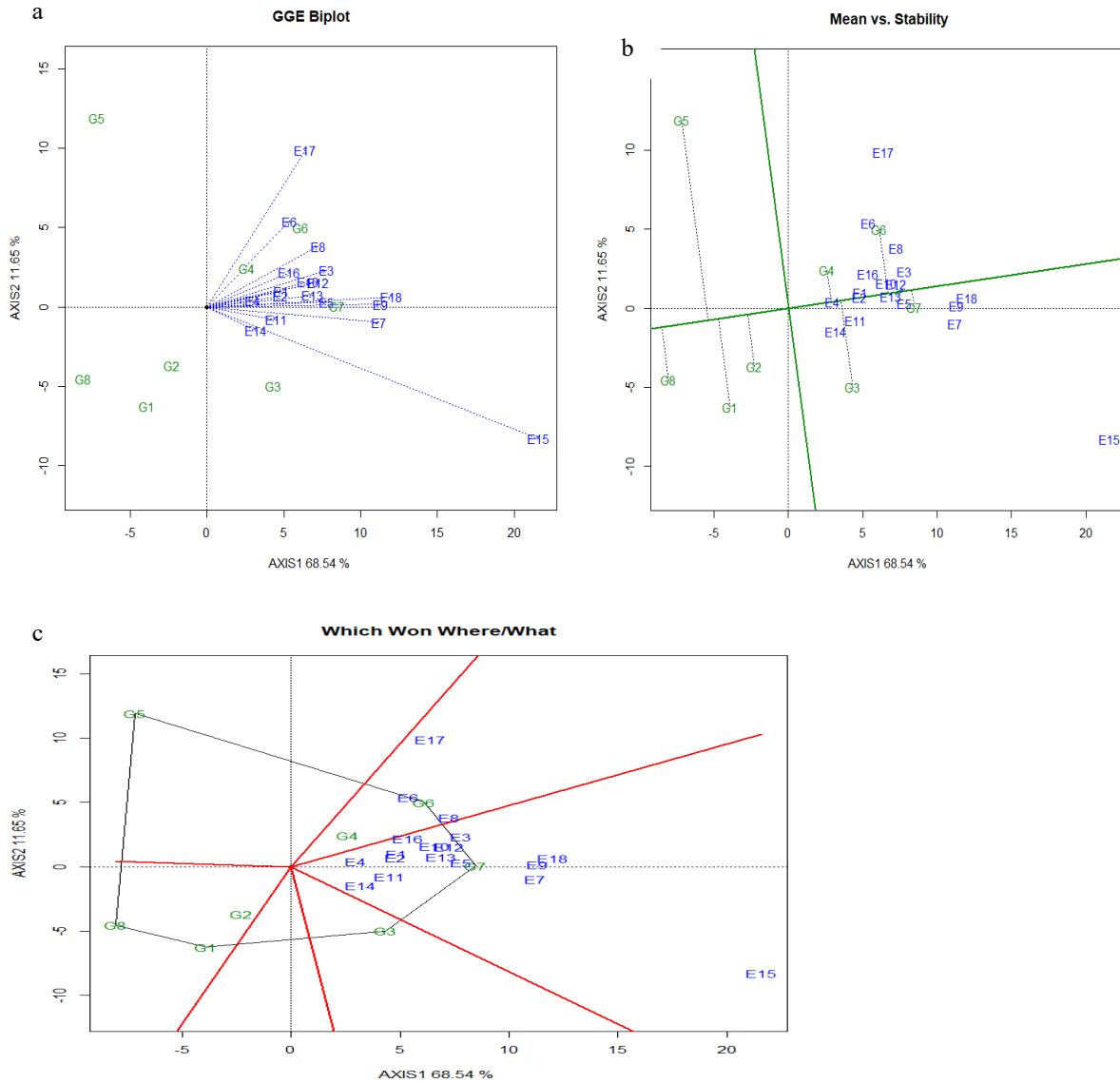


Figure 2a-c. GGE biplot (a), means vs stability (b), and which won where/what (c), and Maize genotypes G1 (SWAN 1 SR-Y), G2 (‘BR-9928-DMR-SR-Y’), G3 (‘OBA SUPER 2’), G4 (DMR-LSR)

Grain Dry Matter Yield

Discriminativeness, ranking environments and genotypes for grain dry matter yield (GDM)

The GGE biplot for grain dry matter yield (Figure 2a) showed that PC1 accounted for 68.54% of the total variation, while PC2 explained an additional 11.65%, resulting in a cumulative variation of 80.19%. The eight genotypes were dispersed into the four quadrants, while the 18 environments were ordinated into Q1 and Q4. The biplot for stover dry matter yield showed the interrelationships among the 18 tested environments (Figure 2b). The environmental vector for maize stover dry matter yield is the line drawn from the biplot origin. The angle between the vectors of two environments represents the association between the two environments. E15 had the longest vector length, followed by E17 and E18, while E4 had the shortest vector length (Figure 2a). The cosine angle between E7 and E15, E8 and E6, E17 and E6 is obtuse. On the other hand, E5 and E18, E4 and E2, and E4 and E13 had the smallest angles (< 90°) between each pair of environments. G4 and E6 are located in the inner circle of the concentric rings. Also, E6 is dispersed close to the concentric ring (Figure 2c and d).

Mean vs stability for grain dry matter yield

The GGE biplot (means vs stability) for grain dry matter yield (Figure 2e) showed the direction of average environment axis from low to high mean values for grain dry matter yield. The maize genotypes were ranked according to their projection and direction from the average environment coordinate. SWAN 1 SR-Y, 'BR-9928-DMR-SR-Y', 'OBA SUPER 2' and 'FARMER'S VARIETY' were ordinated below the average environment axis, while 'DMR-ESR-Y', 'DMR-LSR-Y', 'OBA SUPER 6' and 'LNTP-Y' were dispersed above the average environment coordinate. 'OBA SUPER 6' and 'LNTP-Y' had high grain dry matter yield. 'FARMER'S VARIETY' and 'DMR-ESR-Y' performed poorly for grain dry matter yield. The genotypic performance for grain dry matter yield on the average environment coordinate is similar to the mean values recorded for each genotype (Table 2). 'DMR-ESR-Y' had a long amplitude from average environment axis. 'OBA SUPER 6' had the shortest vector from average environment axis. The vector length of SWAN 1 SR-Y is twice the vector length of 'DMR-ESR-Y'. Furthermore, 'DMR-LSR-Y' was ordinated close to the average environment coordinate abscissa compared to other genotypes. E15, E9, and E18 were dispersed widely from other environments representing contrasting environments (Figure 2e). But E8 and E9, representing different years in each location, were ordinated closer to each other. E6 and E5 were placed on the average environment coordinate abscissa, while other environments showed variable dispersion. The genotypes showed moderate dispersion from average environment axis for grain dry matter yield compared to the environment.

Which won where/what for grain dry matter yield

The polygon showing which won where/what for grain dry matter yield was drawn by connecting data points for the entries further away from the origin; the remainder of the genotypes were dispersed within the polygon (Figure 2f). Eighteen (18) environments were ordinated in two of the six sectors (Figure 2c). Seven environments, viz. E9, E18, E4, E10, E11, and E1 formed one mega-environment while E5, E6, E2, E17, E12, E14, E15, E8, E7, E5, E16 and E3 constitute the second mega-environment. Genotypes found at the vertices of the polygon were 'LNTP-Y', 'DMR-LSR-Y', SWAN 1 SR-Y, and 'FARMER'S VARIETY' while 'OBA SUPER 6', 'OBA SUPER 2', 'OBA SUPER 2,' and 'DMR-ESR-Y' were dispersed within the polygon. 'FARMER'S VARIETY' had the longest vector length in each sector. 'DMR-LSR-Y', SWAN 1 SR-Y, and 'LNTP-Y' are superior for grain dry matter yield in their respective sector, but 'DMR-LSR-Y' had no specific adaptation to any environment. 'LNTP-Y' showed proximity to the first mega environment, while SWAN 1 SR-Y had proximity to the second mega environment. 'DMR-ESR-Y' is superior for stover dry matter yield while 'LNTP-Y' and 'FARMER'S VARIETY' are inferior.

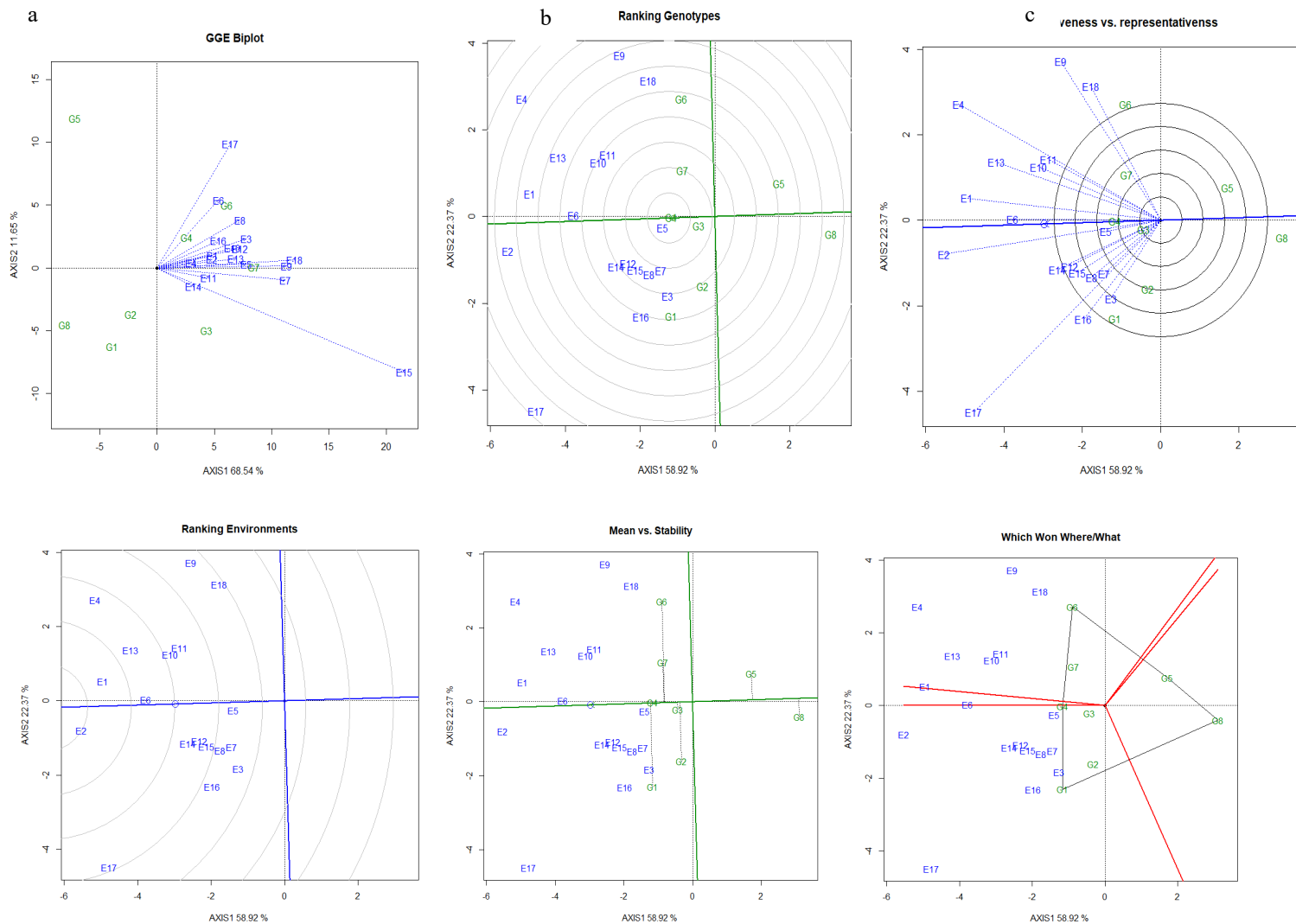


Figure 3a-d. Discriminativeness vs representativeness (a), ranking genotypes (b), means vs stability (c) and which won where/what (d) and Maize genotypes G1 (SWAN 1 SR-Y), G2 ('BR-9928-DMR-SR-Y'), G3 ('OBA SUPER 2'), G4 ('DMR-LSR-Y'), G5 ('DMR-ESR-Y'), G6 ('LNTP-Y'), G7 ('OBA SUPER 6') and "FARMER'S VARIETY" (G8) for grain dry matter yield.

Discussion

This investigation was carried out to select maize breeding lines that outperform the commercial varieties and the check for grain yield, stover dry matter yield, and grain dry matter yield, and the best environment(s) for grain yield, grain dry matter yield, and stover dry matter yield. A highly significant genotypic response ($p \leq 0.01$) for grain yield, grain dry matter yield, and stover dry matter across the 18 environments is attributed to genetic factors, heterogeneity in maize genotypes, differential responses to soil and weather conditions, and variations in response to biotic stress across years and geographic environments. The main effects accounted for a higher proportion of the total variability in grain yield, grain dry matter yield, and stover dry matter. Similar to our findings, Bisawas et al. (2014), Li et al. (2018), and Bocianowski et al. (2019b) found significant GEI for grain yield in maize genotypes. High mean squares due to environment demonstrated that the genotypic response was influenced largely by biotic and weather factors across the testing sites and years. Significant year effects for grain yield, grain dry matter yield, and stover dry matter are connected with large differences in temperature, sunshine hours, humidity, precipitation, and altitude between the years and environments. Therefore, there is a need for continuous evaluation over the years to determine genotypes with stable performance (Tena et al. 2019). The genotype \times year interaction and genotype \times location interaction are crucial for selecting promising genotypes for crop improvement (Aramendiz et al., 2019). A significant genotype \times year interaction for grain yield, grain dry matter yield, and stover dry matter suggests a cross-over performance that is non-additive. The mean values were unstable and responsive to environmental factors in each year and across years. This complicates the selection of superior maize genotypes for the target environments (Bocianowski et al. 2019b). The best approach to mitigate genotype \times year interaction and genotype \times location interaction GEI is to identify more productive genotypes with high stability. The maize genotypes exhibited larger phenotypic variation compared to environment and year effects for grain yield, grain dry matter yield, and stover dry matter. With genotype \times environment interaction in grain yield, it is less likely to predict variability in grain yield considering genotypic response alone. Therefore, selection and recommendation based on phenotypic measurement would be inadequate.

As shown in Figure 1a, the percentage variation explained by PC axes 1 and 2 for GY (88 %) suggests the relevance of the GGE analysis in demonstrating the reliability of the information on the discriminating environment, the relationship among testers (genotypes) based on environmental-centered scaling. E1, E4, E11, E9, and E18, with elevations ranging from 324 m to 570.5 m asl, had greater discriminatory power and are more informative on the performance of grain yield. E13 gives the maximum discriminatory ability, thus an ideal environment for grain yield. (Figure 1b). E5, E12, E3, and E17 with altitudes ranging from 341 m to 535 m asl are self-standing environments with the least response to grain yield and may be treated as unique. In another study, Yan and Rajcan (2002) noted that entries with short vector lengths are less responsive to GYI from specific environments. Environments 10, 5, 4, 17, and 11, with the smallest cosine angles (less than 90°), suggest that similar results on grain yield could be obtained from these environments. However, grain yield from these environments was between 2.28 kg and 3.98 kg. The maize genotypes were dispersed with greater variability in each direction of the average environment axis. 'DMR-LSR-Y' was plotted close to the epicenter of the concentric ring and is close to the ideal genotype for GY, while 'LNTP-Y' and SWAN 1 SR-Y ranked 2nd and 4th (Table 2); they were unstable for grain yield.

The polygon view GY showed that the vertex genotypes, viz. SWAN 1 SR-Y, 'DMR-LSR-Y', 'LNTP-Y', and 'FARMER'S VARIETY' performed best for GY in each sector with moderate stability and most representative genotypes in each sector. The vertex genotypes were adapted to specific mega-environments, while genotypes contained within the polygon were less responsive to specific environments and identified redundant test environments. Hybridization among the vertex genotypes in favour of grain yield will produce high vigour. The ordination of E7, E16, E14, E3 and E12 to one mega-environment, E1, E15 and E8 to second mega-environment, and E10, E13, E5, E17, E2, E4, E11, E6, E18 and E9 to the third mega-environment suggest similarities among environments in each mega-environment with little influence of genotype \times environment interaction and a relatively similar performance for grain yield. Therefore, a single environment in each of the second and third mega-environments should suffice for grain yield. E16 (with 3.26 kg) is a promising environment for grain yield in the first mega-environment; E1 (4.01 kg) showed improved performance compared to E15 and E8 in the second mega-environment. E9 and E18 in the guinea savannah agro-ecology dispersed in the third mega-environment performed best for grain yield with 4.09 Kg and 4.06 Kg, respectively. Therefore, E16, E1, E14, E9, and E18 are promising environments for high grain yield. The Farmer's variety is on the vertex of the unclustered environment with no specific adaptation or with low grain yield across years, and environments cannot be selected for grain yield improvement. SWAN 1 SR-Y, 'DMR-LSR-Y', and 'LNTP-Y' are approved for cultivation in the first, second, and third mega-environments for GY. SWAN 1 SR-Y will repeat the same performance in all the environments in the first

mega environment. The second mega-environment is the ideal environment for harnessing high grain yield in 'DMR-LSR-Y'.

'LNTP-Y' and SWAN 1 SR-Y are sensitive to soil and climatic factors on the average environment axis, with unstable performance for GDM. E18 is the niche environment for 'LNTP-Y', E3 for SWAN 1 SR-Y, and E5 for 'DMR-LSR-Y'. In contrast, "DMR-ESR-Y" and 'FARMER'S VARIETY' were not associated with any environment for grain dry matter yield. The GGE analysis demonstrated that 'DMR-LSR-Y', 'SWAN 1 SR-Y', and 'LNTP-Y' are promising for high grain dry matter yield. However, 'DMR-LSR-Y' is stable and inflexible with high predictability. Some genotypes performed better during 2020 compared to 2021, and vice versa. This is due to differences in sunshine hours, temperature, precipitation, and humidity, which influence the manufacture and partitioning of photo-assimilates. The grouping of the environment into mega-environments is imperative for the simultaneous selection of the entries. This is feasible because environments ordinated in the same mega-environment showed a positive correlation (Yan and Tinker, 2006) with little influence of GEI. Three environments, viz. E9, E1, and E17 in mega-environments one, two, and three, respectively, are ideal environments for attaining higher grain dry matter yield. 'DMR-LSR-Y' is the ideal genotype for GDM in E5, while SUWAN 1 SR-Y is a potential genotype for grain dry matter yield in E3 due largely to high mean performance with moderate variability. The top three genotypes for grain dry matter yield across environments and years are 'DMR-LSR-Y', 'SUWAN 1 SR-Y', and 'LNTP-Y'. Both 'LNTP-Y' and SWAN 1 SR-Y are highly unstable and variable; their selection and recommendation for grain dry matter yield would be inadequate. 'DMR-LSR-Y' is located in the small circle on the average environment coordinate abscissa, which represents the ideal cultivar with the highest dry matter yield and stability across the 18 environments. Therefore, 'DMR-LSR-Y' may serve as a reference cultivar for grain dry matter yield (Figure 3b).

The discriminativeness and representativeness of the eight genotypes for stover dry matter yield in 18 environments demonstrated interrelationships among the environments. E4, E14, E2, and E1 were arranged close to the center of the concentric rings. This indicates that these environments are the best for assessing the stability of stover dry matter yield (Figure 2a-e). E11, E7, E9, and E18 are the most representative, while E17 and E15 are representative of the average environment, unstable, and are characterized by low stover dry matter yield. E15 with a highly discriminating environment is more informative about the performance of the genotypes for stover dry matter yield and could be useful for the identification of superior genotypes. E4 is the least discriminating and independent test environment. Both E4 (in the rain forest agro-ecology with 376 m asl) and E14 (in the northern Guinea savannah) represent the ideal environment and self-standing evaluating stations for stover dry matter yield. This indicates that in these environments, the genotypes were less responsive to GYI. The pair of environments with cosine angles less than 90° had similar responses for VDM. Therefore E15, E9, and E18 were informative in terms of discriminating stover dry matter yield. These environments are within the rain forest and Sudan agro-ecology with close altitudes. The association between E4, E14; E17, E15, and E18 suggests very weak environments that could be treated as independent test environments for stover dry matter yield and therefore are all useful.

The vertex genotypes, viz. 'DMR-ESR-Y', 'FARMER'S VARIETY', SWAN 1 SR-Y, 'OBA SUPER 2', 'OBA SUPER 6', and 'LNTP-Y' showed better performance than other genotypes for stover dry matter yield and were most responsive to the environment within their respective sector. Hybridization among the vertex genotypes in favour of stover dry matter yield will produce high heterosis for stover dry matter yield. 'BR-9928-DMR-SR-Y' and 'DMR-LSR-Y' contained within the polygon were less influenced by a constellation of environmental factors with a positive correlation with the mega environment. Therefore, 'LNTP-Y' showed similar performance for stover dry matter yield in E6 and E8. Also, 'DMR-LSR-Y' recorded similar performance in E17, E8, and E6, while SWAN 1 SR-Y, 'OBA SUPER 2', 'DMR-ESR-Y', and Farmer's variety had no specific adaptation. E17, E6, E8 cluster together in one mega-environment while E1, E2, E3, E4, E5, E7, E9, E10, E11, E12, E13, E14 and E15 to second mega-environment. Genotypes belonging to one mega-environment imply that the environment had a random effect and no adaptation of the genotypes to a specific environment. This is imperative to identify core testing environments and superior genotypes and reduce testing costs. E15 is the best environment for selecting high stover dry matter yield, but it did not indicate that the genotype selected in this environment will be stable. 'DMR-ESR-Y' is superior for stover dry matter yield, while 'LNTP-Y' and Farmer's variety are inferior. 'OBA SUPER 6' and 'LNTP-Y' are superior for stover dry matter yield, while DMR-ESR Y and 'FARMER'S VARIETY' are inferior. The cross-over performance for stover dry matter yield was recorded across the 18 environments and was divided into two mega-environments. This suggests that the environment is not random, with adaptation to a specific environment. Therefore, evaluation for genotypic performance in mega-environments should be based on the mean performance of each genotype across environments and years.

CONCLUSION

In the rainforest, Guinea, and Sudan savannah agro-ecologies, the interaction between genotype and environment poses significant challenges in crop improvement, particularly in the selection and approval of cultivars. The response of the genotypes to the environment and the genotype \times environment interaction influenced grain yield, grain dry matter yield, and stover dry matter yield of maize across 18 environments over two years. The 18 test environments were categorized into three mega-environments for grain yield, grain dry matter, and vegetable dry matter, each demonstrating optimal performance for their respective metrics. Specifically, G1 (SWAN 1 SR-Y) excelled in grain yield, G2 (BR-9928-DMR-SR-Y) stood out for stover dry matter, and G3 (OBA SUPER 2) was the best for grain dry matter. Among the environments, E1 (Ikole-Ekiti) was the top performer for grain yield, E2 (Ara, Ikole Ekiti) excelled in grain dry matter yield, and E3 (Ado-Odo) outperformed others in terms of stover dry matter yield. G1 (SWAN 1 SR-Y), G2 (BR-9928-DMR-SR-Y), and G3 (OBA SUPER 2) are recognized for their stability as high-yielding genotypes and are likely to be excellent sources of alleles for grain yield, grain dry matter yield and stover dry matter yield. This indicates strong grain productivity and the potential for lower grain production costs when these entries are utilized in commercial grain production. The study also highlights E13 (Ayetoro village) as promising for the identification of superior maize genotypes in grain yield, grain dry matter yield and stover dry matter yield. DMR-LSR-Y and LNTP-SR-Y demonstrated the best performance for grain yield and grain dry matter yield. Hybridizing DMR-LSR-Y, LNTP-Y, OBA SUPER 6, and OBA SUPER 2 may lead to the development of a segregating population for grain yield, stover dry matter yield paving the way for the selection of varieties preferred by farmers.

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