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GGE Biplot Analysis of Genotype × Environment Interaction and Yield Stability in Bambara Groundnut

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Abstract: In plant breeding and agricultural research, biplot analysis has become an important statistical technique. The goal of this study was to find the winning genotype(s) for the test settings in a part of the Southwest region of Nigeria, as well as to investigate the nature and extent of genotype × environment interaction (GEI) effects on Bambara groundnut (BGN) production. The experiment was carried out in four environments (two separate sites, Ibadan and Ikenne, for two consecutive years, 2018 and 2019) with ninety-five BGN accessions. According to the combined analysis of variance over environments, genotypes and GEI both had a substantial ($p < 0.001$) impact on BGN yield. The results revealed that BGN accessions performed differently in different test conditions, indicating that the interaction was crossover in nature. The results revealed that BGN accessions performed differently in different test conditions, indicating that the interaction was crossover in nature. To examine and show the pattern of the interaction components, biplots with the genotype main effect and genotype × environment interaction (GEI) were used. The first two PCs explained 80% of the total variation of the GGE model (i.e., G + GE) (PC1 = 48.59%, PC2 = 31.41%). The accessions that performed best in each environment based on the "which-won-where" polygon were TVSu-2031, TVSu-1724, TVSu-1742, TVSu-2022, TVSu-1943, TVSu-1892, TVSu-1557, TVSu-2060, and TVSu-2017. Among these accessions, TVSu-2017, TVSu-1557, TVSu-2060, TVSu-1892, and TVSu-1943 were among the highest-yielding accessions on the field. The adaptable accessions were TVSu-1763, TVSu-1899, TVSu-2019, TVSu-1898, TVSu-1957, TVSu-2021, and TVSu-1850, and the stable accessions were TVSu-1589, TVSu-1905, and TVSu-2048. In terms of discriminating and representativeness for the environments, Ibadan 2019 is deemed to be a superior environment. The selected accessions are recommended as parental lines in breeding programs for grain yield improvement in Ibadan or Ikenne or similar agro-ecological zones.

Keywords: Bambara groundnut; food security; genotype × environment interaction; GGE biplot; multi-environment trial; stability analysis; yield

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1. Introduction

Bambara groundnut (BGN) belongs to the family *Fabaceae* and is commonly grown in sub-Saharan Africa and some parts of Asia [1]. The pod, seed qualities, plant vigor, plant spread, leaf shape, nutritional, and antinutrient components all have a wide range of diversity. Farmers, particularly those in rural communities, benefit from it as a source of revenue. It can be utilized as a human food source and as a livestock feed additive. Reports have emerged that it can be used in the treatment of diseases such as diarrhea [2]. The seeds are rich in protein, carbohydrates, fat, mineral content, and fiber [3,4]. BGN is believed to be the most resilient to drought among grain legumes [5,6]. Wild varieties predominate due to limited research into domesticating new varieties. The major producing/exporting countries are Niger, Ghana, Chad, Nigeria, Mali, Senegal, Côte d'Ivoire, Burkina Faso, and Togo. Some parts of southern Africa also grow the crop; however, Purseglove [7] reported that the most extensive production of the crop in southern Africa is in Zambia.

BGN seeds are not sold on world markets as they are not widely accepted as a major crop yet, but these seeds are an important part of the diet in several countries in West Africa, where they are highly valued. Their consumption in this region is 3rd to only cowpea and peanut according to the national production and consumption statistics [8]. In Ghana specifically, the seeds are canned, which makes them available throughout the year. Over 40,000 cans of different sizes are available. The seeds can be consumed when they are still immature or when fully matured, although matured seeds are hard and not easy to cook; they can, however, be ground into powder before further processing for consumption [9]. To soften them more quickly, they can also be boiled until soft after soaking for a while.

The International Institute of Tropical Agriculture, in Nigeria, retains over 1900 accessions obtained from various countries in their Genetic Resources Center [10]. BGN seeds are nutrient-dense and economically important. Demand for the seeds is high, and supply is limited in their area of cultivation [11]. Despite these benefits, BGN's agro-ecological and genetic potential remains untapped. Instead of agro-ecological or production-specific varieties, it is still grown from local landraces.

Despite intensive national breeding efforts for BGN, there are few studies on yield stability in this agricultural zone, which limits the sustainability of sufficient grain production. Even though BGN yield varies greatly among landraces, no landrace can be considered a true variety [12]. The situation can be improved by breeding crops that produce high yields in a wide range of agro-climatic conditions. However, the potential large interaction with a complex set of bio-physical environments prevailing in a region complicates direct selection for yield in the field [13]. To effectively identify the yield potential of consistently performing BGN accession, yield and stability must be considered simultaneously in a variety of accessions.

Its yield stability and adaptability determine any crop variety's ability to thrive in a given environment. Due to differences in the various environments, these traits are influenced by genotype × environment interactions (GEI). Plant breeders are increasingly interested in GEI to identify long-term solutions to issues controlling plant growth and development. Because of the increasing interest, several statistical methods have been developed for multi-environment trials (MET) to study GEI effects [14,15]. The two most common methods used for MET are additive main effects and multiplicative interaction (AMMI), and genotype plus genotype environment interaction (GGE) biplot [16]. Both methods are used for straightforward graphical representation of a complex genotype by two-way environment tables using principal component analysis [17]. The difference between the two methods is based on how the means are treated before the singular value decomposition (SVD) is performed. With AMMI, SVD is applied to the data excluding genotype and environment means, while GGE biplot excludes from the data the environment means only [18]. According to Alizadeh et al. [16], both methods are highly correlated, and therefore can be used interchangeably.

The biplot and the GGE concepts are used in the GGE biplot method to visually analyze the results of site regression analysis in MET data [19]. The concept of GGE biplot involves the use of biplot to show the two important factors, which are also sources of variation (viz., G and GE). GGE biplot fits best for genotype evaluation (mean vs. stability), test environments which provide discriminating power vs. representativeness, and multi-environment analysis (such as "which-won-where" pattern) [20,21]. GGE biplot is a versatile method with the ability to analyze a range of data types using a two-way structure [22]. Since the introduction of the GGE biplot, numerous applications of the method on MET analysis have been reported. Alake et al. [23] determined the yield stability of 24 BGN landraces using GGE biplot analysis. Elsewhere, GGE biplot analysis of yield stability for Andean dry bean accessions grown under different abiotic stress regimes in Tanzania was reported by Mndolwa et al. [24]. Soybean performance and stability in

MET using GGE biplot analysis was also reported by Dalló et al. [25]. Other applications of GGE biplot have been reported on various crops such as maize [26], sugarcane [27], sunflower [28], rice [17], and wheat [29].

The goals of this study were to examine and quantify the magnitude of GEI effects on BGN yield, as well as to determine the adaptability and stability of the 95 BGN accessions in the studied test environments in Southwest Nigeria.

2. Materials and Methods

2.1. Study Site Descriptions

The study was conducted in two different agroecological zones: Ibadan (7°40′19.62″ N, 3°91′73.13″ E), which is a derived savannah, and Ikenne (6°51′00.873″ N, 3°41′48.528″ E), which is a rain forest. International Institute of Tropical Agriculture (IITA) field stations in Ibadan and Ikenne were used. The study was carried out in the 2018 and 2019 planting seasons. The average climate data for the study sites are shown in Table 1.

Table 1. Monthly mean meteorological data of the experimental sites during BGN growing season (average of 2018–2019 and 2019–2020 crop season).

			August	September	October	November	December	January
Ibadan	2018/2019	Average temperature (°C)	25	25	25	30	30	29
		Average precipitation (mm)	94.8	99.2	53.5	3.3	0	37.6
		Average relative humidity (%)	85	87	86	69	53	62
	2019/2020	Average temperature (°C)	26	26	26	28	29	29
		Average precipitation (mm)	266.7	319.8	661	69.8	1.3	0.9
		Average relative humidity (%)	82	83	85	77	62	46
Ikenne	2018/2019	Average temperature (°C)	26	26	27	28	29	29
		Average precipitation (mm)	113.2	163.9	69.3	13.3	0.6	45.1
		Average relative humidity (%)	87	90	87	86	79	82
	2019/2020	Average temperature (°C)	26	26	26	28	28	28
		Average precipitation (mm)	390.3	300.9	565.8	145.4	12.7	1
		Average relative humidity (%)	85	88	89	85	83	71

2.2. Soil Sampling and Analysis

Topsoil samples were obtained from 0–15 cm over the entire plot using a soil auger and put together to obtain a composite sample before establishing the experiment after the harvest. The soil sample was dried under shade, and passed through a 2 mm sieve for subsequent chemical analyses (sand, clay, silt, pH, organic carbon (OC), total N, exchangeable Ca, Mg, K, available P, Na, Mn, Cu, Fe, and Zn) and particle size distribution at the onset of the experiment.

2.3. Plant Materials, Field Trials, and Yield Data Collection

A set of 95 accessions out of the BGN germplasm that was housed at the Genetic Resources Centre, IITA, Ibadan, Nigeria, was used in this study (Table 2).

The accessions were evaluated using randomized complete block design. Sixty seeds of each accession were planted during the 2018 and 2019 planting seasons. The accessions were planted in three replicates, with each replicate having 20 plants per accession on a plot, which were later thinned to 10 plants at 2 weeks after emergence. The length of each plot was 3 m, with 0.3 m spacing between each plant and a row spacing of 0.7 m between each plot. Each replicate contained 3 blocks, which were separated by 1 m spacing, and the replicates were separated from one another by 2 m spacing. The first planting in 2018 was on 1 and 12 September, while that of the 2019 season was on 26 August and 16 September, in Ikenne and Ibadan, respectively. Plants were rain fed until the stop of rain, then irrigation was applied once a week until harvest. The 2018 planting was harvested on 2 and 18 January 2019, while the 2019 harvesting was done on 11 and 15 January 2020, for

Ikenne and Ibadan, respectively. Seeds were weighed to obtain the total seed weight per plot, which was then converted to kg/ha using the following formula:

$$\text{Yield}(\text{kg}/\text{ha}) = \frac{\text{plot yield}*10,000}{\text{plot area}}$$

Table 2. Bambara groundnut accessions and their origin.

	Accessions	Passport Data		Accessions	Passport Data		Accessions	Passport Data
1	TVSu-1470	Ghana	33	TVSu-1866	Zimbabwe	65	TVSu-2017	Burundi
2	TVSu-1538	unknown	34	TVSu-1868	Zimbabwe	66	TVSu-2018	Burundi
3	TVSu-1547	unknown	35	TVSu-1874	Botswana	67	TVSu-2019	Burundi
4	TVSu-1557	unknown	36	TVSu-1879	Botswana	68	TVSu-2020	unknown
5	TVSu-1574	unknown	37	TVSu-1892	Botswana	69	TVSu-2021	unknown
6	TVSu-1589	unknown	38	TVSu-1895	Botswana	70	TVSu-2022	unknown
7	TVSu-1649	Senegal	39	TVSu-1898	Unknown	71	TVSu-2025	unknown
8	TVSu-1663	Senegal	40	TVSu-1899	Unknown	72	TVSu-2030	unknown
9	TVSu-1664	Senegal	41	TVSu-1905	Unknown	73	TVSu-2031	unknown
10	TVSu-1680	Togo	42	TVSu-1912	Cameroon	74	TVSu-2032	unknown
11	TVSu-1701	Togo	43	TVSu-1915	Cameroon	75	TVSu-2034	unknown
12	TVSu-1706	Zambia	44	TVSu-1918	Cameroon	76	TVSu-2038	unknown
13	TVSu-1724	Zambia	45	TVSu-1920	Senegal	77	TVSu-2042	unknown
14	TVSu-1733	Zambia	46	TVSu-1921	Malawi	78	TVSu-2043	unknown
15	TVSu-1739	Zambia	47	TVSu-1923	Zimbabwe	79	TVSu-2045	unknown
16	TVSu-1740	Zambia	48	TVSu-1930	Zimbabwe	80	TVSu-2046	unknown
17	TVSu-1742	Zambia	49	TVSu-1937	Zimbabwe	81	TVSu-2048	unknown
18	TVSu-1745	Malawi	50	TVSu-1939	Zimbabwe	82	TVSu-2051	unknown
19	TVSu-1758	Malawi	51	TVSu-1941	Zimbabwe	83	TVSu-2055	unknown
20	TVSu-1763	Malawi	52	TVSu-1943	Zimbabwe	84	TVSu-2056	unknown
21	TVSu-1764	Malawi	53	TVSu-1945	Zimbabwe	85	TVSu-2060	unknown
22	TVSu-1765	Malawi	54	TVSu-1951	Zimbabwe	86	TVSu-2065	unknown
23	TVSu-1785	Malawi	55	TVSu-1952	Zimbabwe	87	TVSu-2067	unknown
24	TVSu-1787	Cameroon	56	TVSu-1956	Zimbabwe	88	TVSu-2068	unknown
25	TVSu-1823	Niger	57	TVSu-1957	Zimbabwe	89	TVSu-2071	unknown
26	TVSu-1836	Niger	58	TVSu-1959	Swaziland	90	TVSu-2074	unknown
27	TVSu-1839	Zimbabwe	59	TVSu-1962	Swaziland	91	TVSu-2075	unknown
28	TVSu-1843	Zimbabwe	60	TVSu-1964	DRC	92	TVSu-2076	unknown
29	TVSu-1850	Zimbabwe	61	TVSu-1972	DRC	93	TVSu-2083	unknown
30	TVSu-1851	Zimbabwe	62	TVSu-1979	Burundi	94	TVSu-2085	unknown
31	TVSu-1859	Zimbabwe	63	TVSu-2000	Burundi	95	TVSu-2086	unknown
32	TVSu-1863	Zimbabwe	64	TVSu-2003	Burundi			

2.4. Statistical Analysis

The analysis of yield data was carried out using the R statistical package [30]. The yield data were subjected to analysis of variance (ANOVA) after the data had been normalized by log-transforming. Each year at each location was considered as a separate environment.

In this study, Eberhart and Russell's joint regression model was used for the stability analysis. Eberhart and Russell's [14] model uses joint linear regression where the yield of each genotype is regressed on the environmental index. The behavior of the genotype was determined by the following model: $Y_{ij} = \mu_i + \beta_i I_j + \delta_{ij}$.

In the above model, Y_{ij} = the mean performance of the ith genotype in the jth environment, μ_i = the grand mean of the ith genotype over all the environments, β_i = the regression coefficient which measures the response of the ith genotype on the environmental index, I_j = the environmental index obtained by the difference between the mean of each environment and the grand mean, and δ_{ij} = the deviation from the regression of the ith variety in the jth environment.

If there was a significant difference in genotype–environment interaction, the GGE biplot method was employed to analyze and assess the interaction and yield stability. The GGE biplot was constructed using the first two principal components (PC1 and PC2) derived using environment-centered yield data [31]. GEA-R version 4.1 [32] was used to analyze GGE biplot and stability analysis. SVD of the first two principal components was used to fit the GGE biplot model [33]:

$$Y_{ij} = \mu + \beta_j + \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij}$$

where Y_{ij} is the trait mean for genotype i in environment j; μ is the grand mean; β_j is the main effect of environment j; $\mu + \beta_j$ is the mean yield across all genotypes in environment j; λ_1 and λ_2 are the singular values (SV) for the first and second principal components (PC1 and PC2), respectively; ξ_{i1} and ξ_{i2} are eigenvectors of genotype i for PC1 and PC2, respectively; $\eta_1 j$ and $\eta_2 j$ are eigenvectors of environment j for PC1 and PC2; and ε_{ij} is the residual associated with genotype i in environment j. In GGE biplot analysis, scores of PC1 were plotted against PC2 [20].

Accordingly, GGE biplot analysis was also used to generate graphs for the (i) mean performance and stability analysis, (ii) which-won-where pattern, (iii) relationship among test locations, and (iv) ranking discrimination and representativeness of test locations. Angles between location vectors in GGE biplot were used to judge the correlation between pairs of locations [19].

3. Results and Discussion

3.1. Soil Analysis

Soil physicochemical properties for the two locations in both seasons are presented in Table 3. Higher amounts of sand, calcium, magnesium, potassium, sodium, manganese, iron, copper, and zinc were recorded in Ikenne compared to Ibadan for the 2018 planting season, while in the 2019 planting season, Ibadan had the highest pH, sand, nitrogen, organic carbon, manganese, iron, and zinc when compared with Ikenne (Table 3). Different soil properties were recorded at both locations for both years.

Table 3. Soil properties at the beginning of the experiment for individual locations and seasons.

Properties	2018		2019	
	Ibadan	Ikenne	Ibadan	Ikenne
Sand%	73.67	80.33	79.33	75.00
Clay%	19.67	13.67	14.00	15.67
Silt%	6.67	6.00	6.67	9.33
pH	6.70	6.42	6.59	5.02
%N	0.17	0.10	0.10	0.09
Bray P	13.45	22.48	11.27	18.89
%OC	1.02	0.41	0.44	0.41
Ca (cmol/kg)	1.13	3.53	1.19	3.53
Mg (cmol/kg)	0.07	0.80	0.27	0.80
K (cmol/kg)	0.14	0.56	0.22	0.56
Na (cmol/kg)	0.06	0.08	0.05	0.08
Mn (ppm)	150.39	154.82	135.30	112.15
Fe (ppm)	86.22	85.84	89.46	85.58
Cu (ppm)	0.55	1.17	0.20	1.17
Zn (ppm)	1.05	1.96	2.72	1.96

Crop yield has been shown to be influenced by soil and climatic conditions. Crops respond differently to various soil types [34]. BGN produces well in sandy soils. Even though sandy soil inhibits crop emergence, BGN benefits from it because it bears fruit underground. Sandy soil has a porous structure with large pores, allowing pods to grow. When sandy soils dry out, they produce thin, loose fissures [35]. This is an advantageous trait, especially in the semi-arid tropics, where rainfall is unpredictable and soil is subjected to prolonged periods of dryness. Although clay soil has a high water-retention capacity, it expands when wet and contracts when dry over long periods of time [36].

3.2. Pooled Analysis of Variance

To check for a significant GEI, analysis of variance was performed (Table 4). Finding the most suitable genotypes for yield improvements is quite difficult due to the GEI's large impact on yield. To produce successful breeding strategies for complex and highly quantitative traits like grain yield in BGN, breeders must quantify GEI. An identifiable and distinct selection pressure was brought to bear in each environment due to varying environmental factors, such as topography and climate. If an adaptation based on environment is ignored, then an overall mean that disregards it would be misleading. Therefore, in order to produce quality results, the method of selection should consider both genotype and environmental factors. According to Bhartiya et al. [37], the number of years of an experiment should be prioritized over the number of locations, and genotype–environment interactions should be considered for the selection of superior genotypes [38,39]. The accessions and environments on their own displayed significant level of variability in their yield responses at $p < 0.001$ and $p \leq 0.05$, respectively, while the GEI effect was significant at $p < 0.001$. This indicates that the accessions do not show consistent performance across the studied environments. The present findings agree with those of Chibarabada et al. [40], who found significant interaction between site and species for BGN grain yield.

Table 4. Analysis of variance for yield data obtained from BGN trials conducted in Ibadan and Ikenne in 2018 and 2019 (environments constitute year–location combinations).

Source of Variations	Df	Sum Sq.	Mean Sq.	F Value	Pr (>F)	
ENV	3	6.146	2.04878	2.9675	0.09717	.
REP(ENV)	8	5.523	0.69041	4.7362	1.10×10^{-5}	***
GEN	94	43.182	0.45938	3.1513	$<2.2 \times 10^{-16}$	***
ENV: GEN	282	55.903	0.19824	1.3599	0.0007	***
Residuals	752	109.622	0.14577			

Coefficient of variation = 0.39. DF = Degree of freedom. Sum sq. = sum of squares. Mean sq. = mean square. . Significant at $p \leq 0.05$. *** Significant at $p < 0.001$.

3.3. Stability Analysis

Following the Eberhart and Russell [14] method, the stability of the accessions across the environments was analyzed (Table 5 and Figure 1). Becker and Léon [41] reported that genotypes having bi = 0 are not affected by environmental factors; thus, they are said to be stable, while those showing average responses possess bi = 1. On the other hand, Eberhart and Russell [14] proposed that genotypes are stable if they show high mean performances, their regression coefficient equals 1, and their deviation from regression is as low as possible.

Coefficient of variation (CV) analysis showed 22 out of the 95 accessions as highly productive and stable (Figure 1A). TVSU-1763, TVSU-1850, TVSU-1898, TVSU-1899, TVSU-1957, TVSU-2019, and TVSu-2021 were the best-adapting accessions, while TVSU-1589, TVSU-1905, and TVSU-2048 were the most stable accessions, according to Eberhart and Russell's model (Figure 1B). In this study, none of the accessions were recorded to be adaptable and stable in the environments tested.

3.4. GGE Biplot Analysis

GGE biplot allows environment evaluation based on the discriminating ability and representativeness of the GGE view [42]. This ability gives it an edge over the AMMI biplot analysis [43]. The GGE biplot analysis was used to identify the best accessions for each environment and assess their stabilities. The relationship among the test environments was modelled based on environment-centered (centering, 2) and environment-metricpreserving (SVP, 2) without scaling option in the GEA-R software. The biplot explained 80% of the total variation observed, of which 48.59% was explained by the first principal component (axis1), while the second principal component (axis2) explained 31.41%. Any test environment's capability can be visualized by examining the environment's discriminating power and representativeness [44]. The length of the environment vectors is proportional to the standard deviation within each biplot's environment and indicates the environment's ability to discriminate [45]. From the biplot analysis (Figure 2A) and representation of the accessions in the various environments (Figure 2B), none of the environments are close to the mean environment (Figure 2B). Accession performance in each environment is shown in Figure 3. For the four environments, most of the accessions are clustered close to the average yield, especially in both IB2018 and IB2019 environments. IK2018 and IK2019 are also clustered to the average yield but have a clearer distinction than the other two environments.

Table 5. Mean and stability analysis for the accessions based on Eberhart and Russell method.

Accessions	Mean	Sd	CV (%)	bi	S2di	Accessions	Mean	Sd	CV (%)	bi	S2di
TVSu-1470	8.32	0.36	4.35	0.42	0.15	TVSu-1937	8.26	0.27	3.27	1.75	0.03
TVSu-1538	8.12	0.23	2.82	1.44	0.01	TVSu-1939	8.16	0.08	0.94	−0.03	−0.04
TVSu-1547	8.40	0.26	3.10	1.76	0.02	TVSu-1941	8.05	0.20	2.53	2.08	−0.03
TVSu-1557	8.61	0.34	3.93	−1.91	0.08	TVSu-1943	8.51	0.54	6.39	3.64	0.25
TVSu-1574	8.21	0.28	3.45	2.06	0.03	TVSu-1945	8.13	0.14	1.74	−1.39	−0.04
TVSu-1589	8.29	0.21	2.54	2.46	−0.05	TVSu-1951	8.43	0.24	2.81	2.11	−0.01
TVSu-1649	8.24	0.33	4.00	1.30	0.10	TVSu-1952	8.17	0.50	6.12	3.99	0.15
TVSu-1663	8.33	0.14	1.65	1.35	−0.04	TVSu-1956	8.26	0.22	2.63	−1.70	−0.01
TVSu-1664	8.03	0.34	4.22	0.79	0.12	TVSu-1957	8.15	0.28	3.43	2.60	0.00
TVSu-1680	8.19	0.30	3.65	1.74	0.05	TVSu-1959	8.38	0.19	2.31	1.92	−0.03
TVSu-1701	8.18	0.17	2.04	−0.74	−0.01	TVSu-1962	8.16	0.24	2.98	1.12	0.03
TVSu-1706	8.16	0.11	1.40	0.54	−0.03	TVSu-1964	8.14	0.49	5.96	1.90	0.27
TVSu-1724	7.95	0.25	3.10	2.17	−0.01	TVSu-1972	7.97	0.21	2.67	0.87	0.01
TVSu-1733	8.35	0.18	2.16	−0.56	0.00	TVSu-1979	8.24	0.12	1.50	1.23	−0.04
TVSu-1739	8.36	0.10	1.17	−0.19	−0.03	TVSu-2000	8.20	0.27	3.24	0.92	0.05
TVSu-1740	8.16	0.21	2.52	1.99	−0.03	TVSu-2003	8.50	0.28	3.27	0.30	0.07
TVSu-1742	8.37	0.47	5.58	3.35	0.16	TVSu-2017	8.56	0.39	4.59	−1.40	0.16
TVSu-1745	8.45	0.29	3.46	0.64	0.08	TVSu-2018	8.35	0.27	3.25	2.66	−0.01
TVSu-1758	8.26	0.27	3.24	1.40	0.04	TVSu-2019	8.62	0.30	3.45	2.98	−0.01
TVSu-1763	8.44	0.39	4.63	4.13	0.00	TVSu-2020	8.16	0.33	3.99	1.68	0.08
TVSu-1764	8.09	0.25	3.12	1.51	0.02	TVSu-2021	8.08	0.28	3.44	2.35	0.01
TVSu-1765	8.29	0.18	2.17	1.76	−0.03	TVSu-2022	8.33	0.49	5.93	4.28	0.12
TVSu-1785	8.23	0.12	1.50	0.85	−0.03	TVSu-2025	7.86	0.42	5.33	3.21	0.10
TVSu-1787	8.03	0.35	4.36	1.39	0.11	TVSu-2030	8.13	0.47	5.73	3.49	0.15
TVSu-1823	8.04	0.19	2.32	−0.06	0.00	TVSu-2031	8.26	0.18	2.22	−0.23	0.00
TVSu-1836	8.15	0.14	1.73	1.40	−0.04	TVSu-2032	8.04	0.16	1.96	0.72	−0.02
TVSu-1839	8.28	0.12	1.46	−0.89	−0.04	TVSu-2034	8.18	0.24	2.97	−0.99	0.03
TVSu-1843	8.44	0.29	3.39	−1.98	0.03	TVSu-2038	8.49	0.19	2.20	−1.32	−0.02
TVSu-1850	8.01	0.25	3.16	2.18	0.00	TVSu-2042	8.31	0.24	2.92	−1.52	0.02
TVSu-1851	7.63	0.29	3.80	1.46	0.05	TVSu-2043	8.40	0.25	2.93	−1.06	0.03
TVSu-1859	8.04	0.27	3.32	2.90	−0.03	TVSu-2045	8.39	0.12	1.37	0.57	−0.03
TVSu-1863	8.03	0.33	4.09	2.76	0.03	TVSu-2046	8.60	0.46	5.34	2.43	0.20
TVSu-1866	8.15	0.51	6.24	4.94	0.08	TVSu-2048	8.14	0.05	0.60	−0.16	−0.05
TVSu-1868	7.88	0.20	2.54	0.59	0.01	TVSu-2051	8.19	0.13	1.54	0.91	−0.03
TVSu-1874	8.36	0.08	0.97	0.33	−0.04	TVSu-2055	8.37	0.21	2.47	1.33	0.00
TVSu-1879	7.99	0.20	2.45	0.30	0.01	TVSu-2056	8.62	0.36	4.20	1.15	0.13
TVSu-1892	8.73	0.36	4.10	0.98	0.13	TVSu-2060	8.58	0.30	3.50	−0.79	0.08
TVSu-1895	7.93	0.07	0.83	0.25	−0.04	TVSu-2065	8.27	0.24	2.95	−0.66	0.04
TVSu-1898	8.17	0.29	3.53	2.68	0.00	TVSu-2067	8.27	0.13	1.61	0.64	−0.03
TVSu-1899	8.02	0.35	4.31	3.79	−0.02	TVSu-2068	8.43	0.09	1.12	0.34	−0.04
TVSu-1905	8.39	0.04	0.47	−0.27	−0.05	TVSu-2071	8.46	0.18	2.11	0.67	−0.01
TVSu-1912	8.36	0.05	0.65	−0.13	−0.04	TVSu-2074	8.48	0.21	2.52	−0.98	0.01
TVSu-1915	8.34	0.17	2.04	0.66	−0.01	TVSu-2075	8.42	0.27	3.15	0.18	0.06
TVSu-1918	8.24	0.20	2.43	−1.25	−0.01	TVSu-2076	8.41	0.20	2.39	0.22	0.01
TVSu-1920	8.54	0.12	1.39	−0.31	−0.03	TVSu-2083	8.26	0.12	1.50	0.21	−0.03
TVSu-1921	8.50	0.25	2.91	0.43	0.04	TVSu-2085	8.34	0.26	3.08	0.44	0.05
TVSu-1923	8.53	0.30	3.54	2.15	0.04	TVSu-2086	8.19	0.17	2.07	−0.62	−0.01
TVSu-1930	8.34	0.14	1.68	0.36	−0.02						

Sd = Standard deviation, CV = coefficient of variation, bi = Regression coefficient, S2di = Standard deviation from linearity of regression.

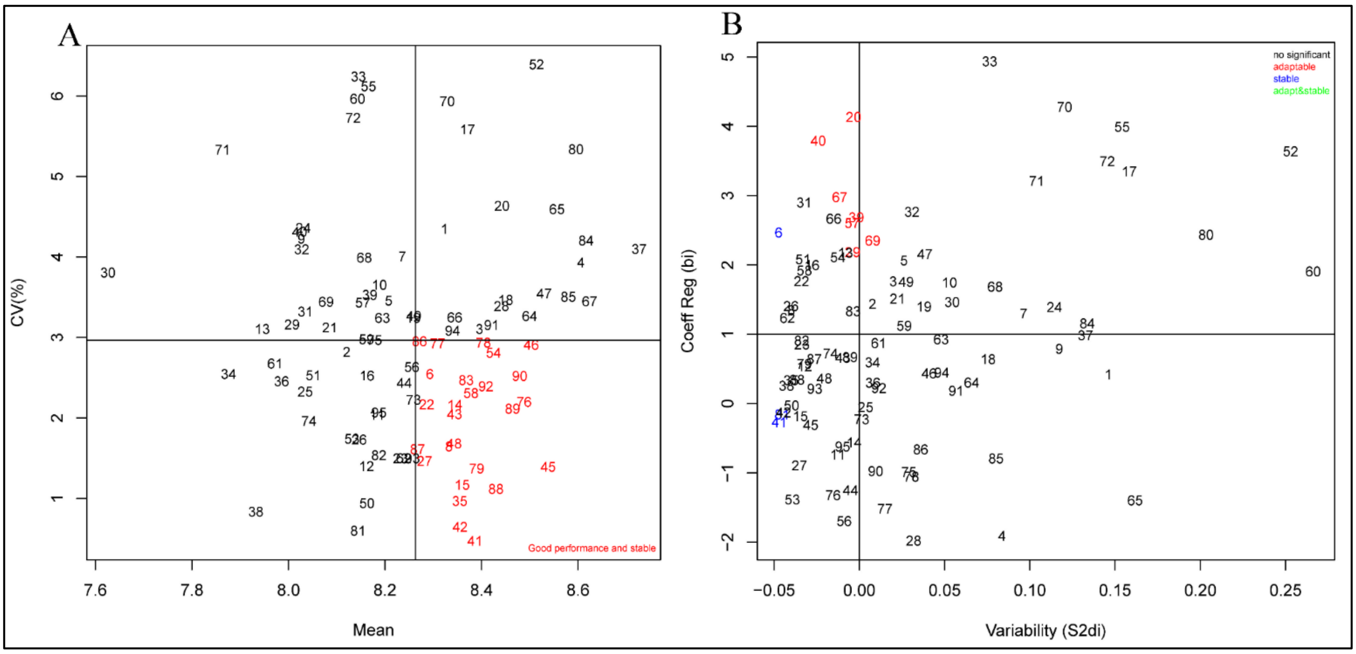

Figure 1. Stability analysis of the accessions with the environments. (**A**) Francis (CV) vs. (**B**) mean biplot for grain yield. Eberhart and Russell (bi, S2di) biplot for grain yield.

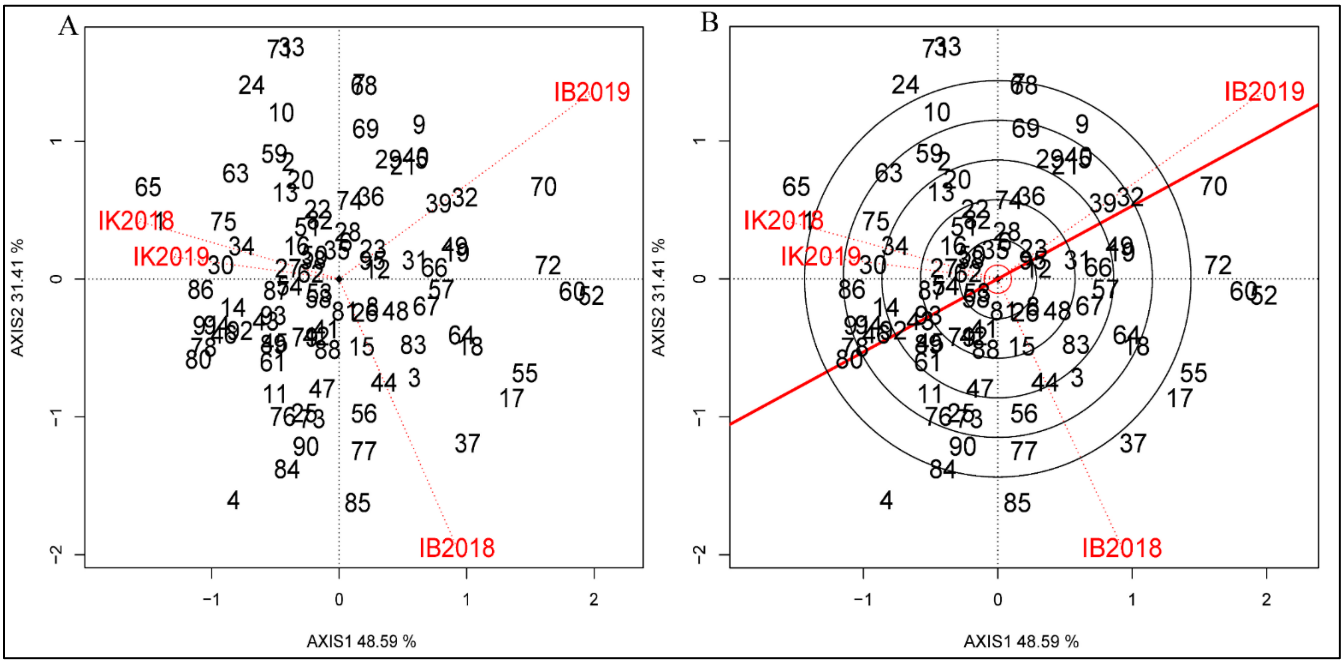

Figure 2. (**A**) Biplot analysis result. (**B**) Discriminativeness and representativeness of the accessions with the environments.

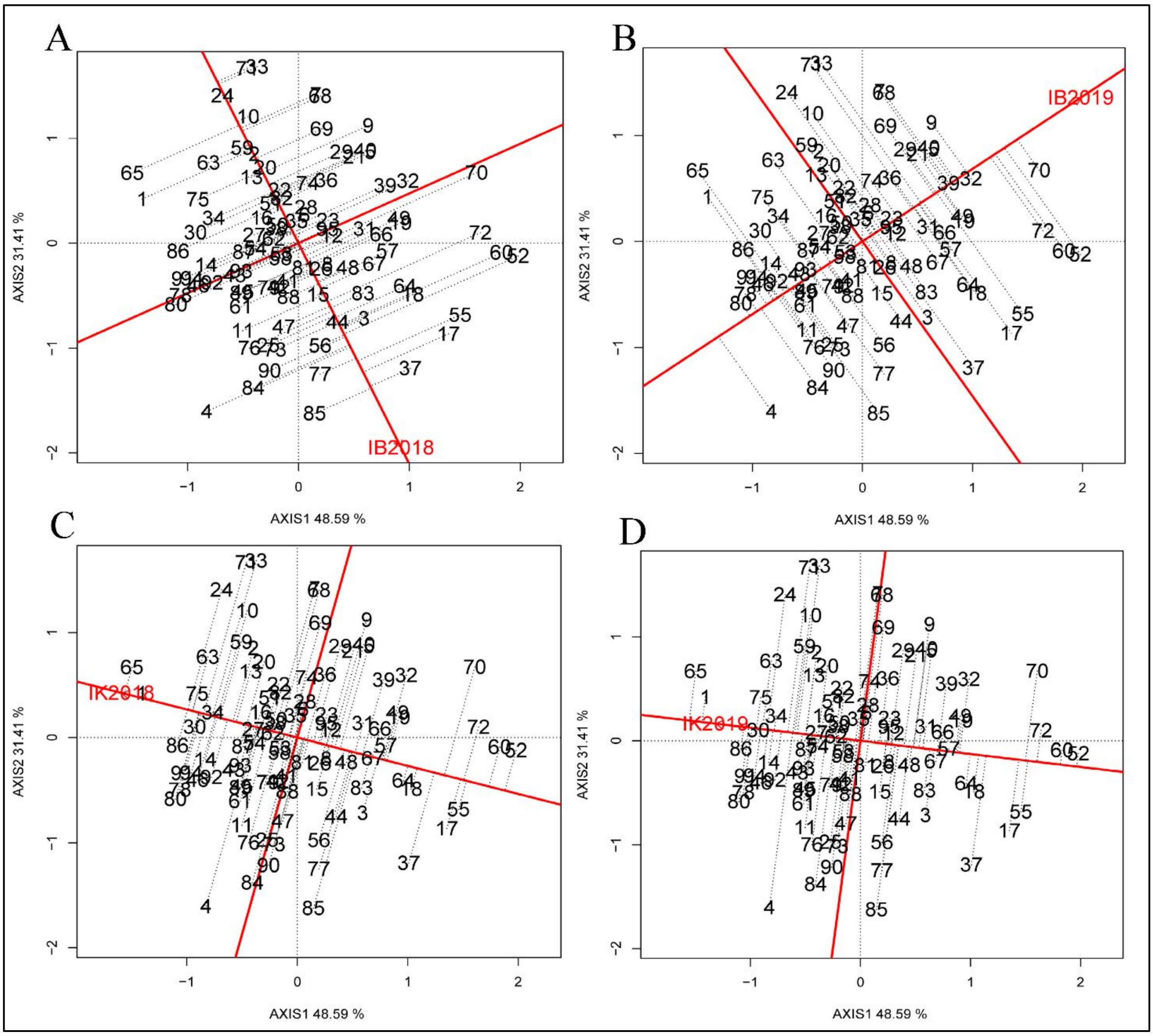

Figure 3. Evaluation of the performances of accessions in the tested environments: (**A**) Ibadan 2018, (**B**) Ibadan 2019, (**C**) Ikenne 2018, and (**D**) Ikenne 2019.

The use of the polygon view of the "which-won-where" biplot is a key component of the GGE, which helps to visualize the interaction patterns between genotypes and environments, to show the presence of crossover GEI, mega-environment differentiation, and specific adaptation [45]. Accessions TVSu-1866, TVSu-2022, TVSu-2017, TVSu-1943, TVSu-1892, TVSu-2060, and TVSu-1557 were all situated at the corners of the polygon (Figure 4), indicating that these accessions were outstanding in terms of their yield in those environments. Accessions/genotypes at the corners of the polygons in a "which-won-where" polygon are the outstanding accessions/genotype in that environment [45]. Among these accessions, TVSu-1943 was the highest-yielding accession in all test environments. Some accessions such as TVSu-1706, TVSu-2018, TVSu-1785, TVSu-1895, and TVSu-1951 were located close to the center of the GGE biplot. This indicates that they showed a stable performance across the test sites [45]. The result in Figure 4 indicates three mega-environments: IB2019, IB2018, and IK2018 and IK2019 together forming the third environment.

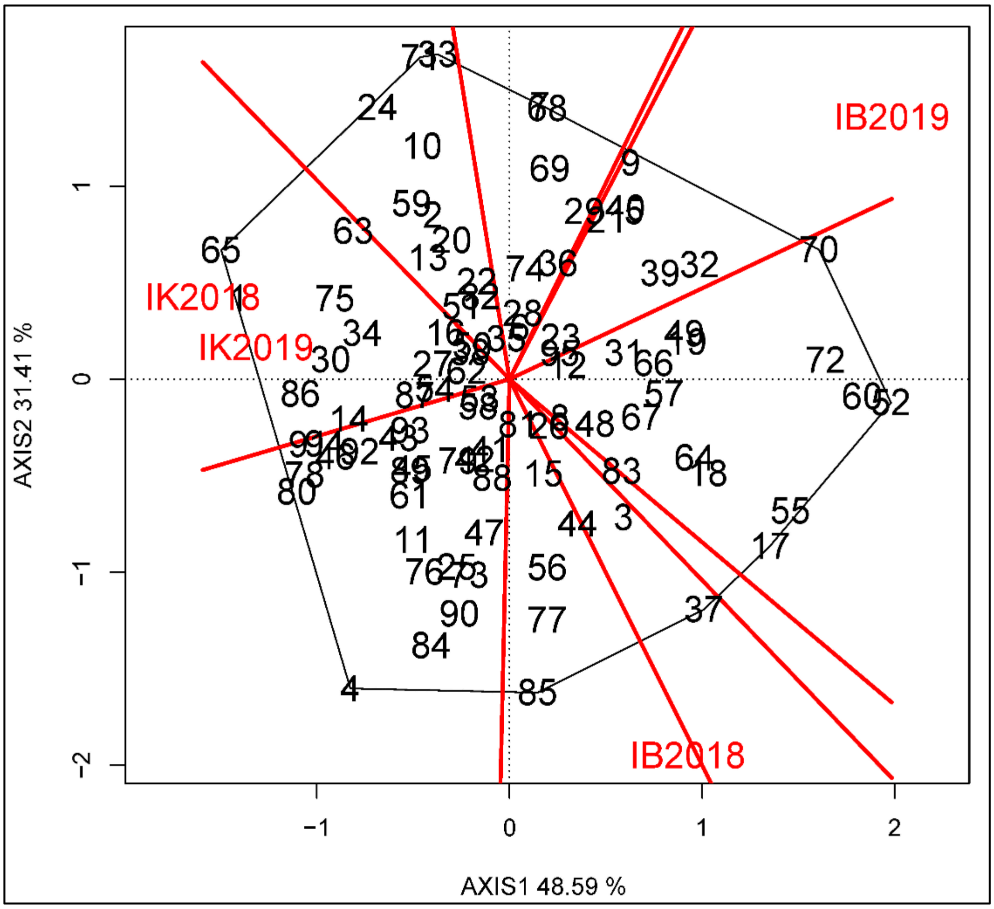

Figure 4. Which-won-where analysis of the accessions. Identifying the best accessions suitable for each test environment.

Figure 5 shows the comparison plot for environments and accessions. Ideal environments and accessions are those which are near or at the center of the concentric circle. Therefore, in this study, the plot in Figure 5A reflected that IB2019 is the closest to being an ideal environment, while TVSu-2020 and TVSu-1649 are the ideal accessions, as shown by their positions (Figure 5B), followed by accessions TVSu-2021, TVSu-1664, TVSu-1866, and TVSu-2025. Accessions close to the ideal accessions are also said to be good. However, accessions TVSu-1557, TVSu-2060, TVSu-2056, and TVSu-2042 are the worst accessions, as they are located far from the concentric circle. In the relationship among the environments, all the environments are positively correlated to one another, but IK2018 and IK2019 are more highly correlated with one another than all the other environments (Figure 5C).

High nutrient uptake, ability to compete favorably with weeds, and yield improvement are some of the prerequisites for developing high-yield crops. The significant differences and the high coefficient of variation observed (39%) (Table 3) indicate the existence of variability in the selected population that can be exploited for an improved breeding program. Variability in traits aid in the trait-assisted selection of best lines for improvement [46,47]. This result is supported by the studies of Olukolu et al. [48] and Gbaguidi et al. [49]. Various studies have shown the GEI effect on several crops such as cassava [50], rice [51,52], sweet potato [53], and sorghum [54]. Yan and Kang [19] stated that the number of genotypes and environments determines the extent of environmental variation. However, according to Aremu et al. [55], the environment is always the dominant source of variation, and it must be prioritized in plant breeding.

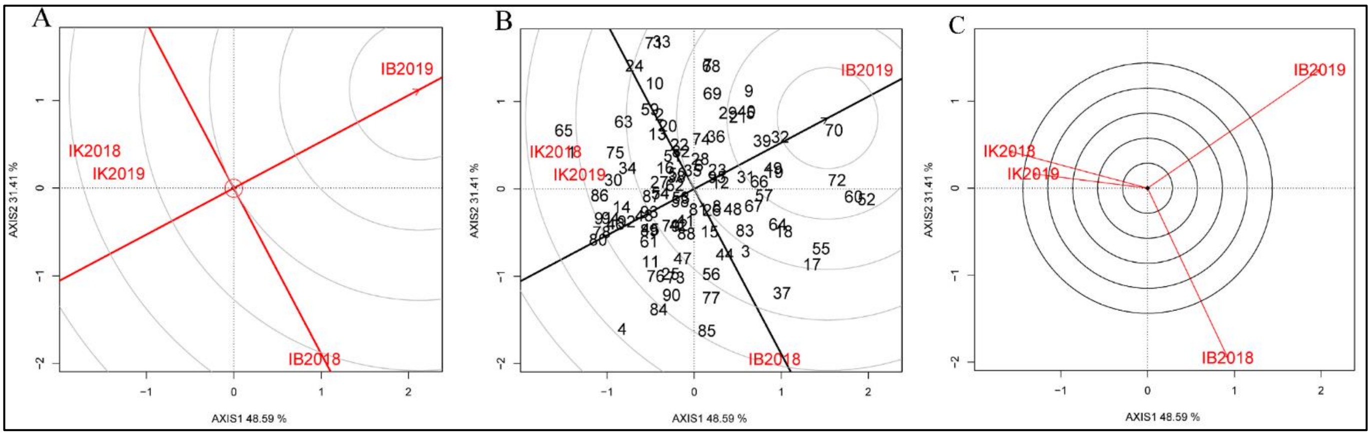

Figure 5. Ranking environments and genotypes based on both mean and stability relative to an ideal genotype. (**A**) Ranking environments with respect to an ideal environment. (**B**) Ranking genotypes with respect to an ideal genotype. (**C**) Relationship among tested environments.

Stability and adaptability are important factors in determining the production efficiency of plant varieties. An accession can be good if it has high grain production and potential for improving its production even in varying environments [56]. Thus, adaptability and stability evaluation are important in improving crop production. GGE biplot is effective in analyzing stability and adaptability in MET [57].

Selection of test environments should consider the discriminating ability due to genotype differences and representative ability to represent target environments [37,58]. In the present study, IB2019 has a longer vector and the smallest angle with an ideal environment, so it is identified in this study as a perfect test environment in terms of being more discriminating and most representative of the overall test environments.

4. Conclusions

First, the number of environments and agro-ecological zones can be increased to allow for greater diversity in test locations. This will aid in drawing more accurate conclusions from the outputs. Second, because there have been few or no reports of MET in BGN yield using GGE biplot, many accessions can be used for research. Finally, this study identified genotypes that are uniquely adapted to each environment by observing how different genotypes performed in each of these locations. This knowledge will enable breeders to advise farmers appropriately on which accession to use where, provided that the various accessions meet the end-user quality preferences. Thus, stability analyses aided in the discovery of unique genotypes for all environments studied, as well as a stable genotype that can be cultivated in all the environments studied and in areas with similar characteristics to the test environments. This can be used as a preliminary study for future breeding programs.

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