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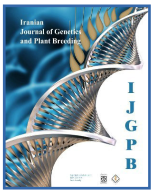

Association studies and yield stability analysis of fonio (*Digitaria iburua Kippis* Stapf) genotypes in Nigeria

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ABSTRACT

Correlation and Path analysis were applied to study the association between yield and various traits in fonio. The Additive Main Effects and Multiplicative Interaction (AMMI) model, alongside Genotype Plus Genotype-by-Environment Interaction (GGE) biplot analysis were used to assess the stability and adaptability of fonio populations across nine locations in Nigeria during the 2022 and 2023 growing seasons. The study evaluated twelve genotypes and one local check, arranged in a randomized complete block design with three replications. Planting was standardized with a spacing of 20 cm×20 cm on plots measuring 3 m×4 m. Significant variability was observed within the population, highlighting substantial potential for genetic improvement. Key traits, including plant height, spike length, panicle length, and the number of spikes per plant, exhibited strong positive phenotypic correlations (0.989, 0.973, 0.977, 0.991, respectively) and genotypic correlations (0.991, 0.974, 0.98, 0.993, respectively) with grain yield, suggesting these traits are primarily governed by genetic factors. Among the evaluated genotypes, IBPL05-19-03 consistently achieved high grain yields across the locations, demonstrating broad environmental adaptability and suitability for diverse conditions. Also, genotype IBPL04-06-04 displayed limited adaptability, making it more suitable for specific micro-environments. Furthermore, genotypes IBPL02-12-01, IBPL04-15-08, IBPL05-19-03, IBPL02-04-02, and IBPL05-07-09 showed stability and general adaptability across varying environments, as evidenced by slope values near 1. The trait-relationship analysis indicated that breeding programs targeting improvements in plant height, panicle length, and tillering capacity could lead to significant yield advancements in fonio. The integration of AMMI and GGE models provided a robust statistical framework in analyzing fonio lines, enabling informed selection and development of genotypes that are both high-yielding and environmentally stable across diverse agro-ecological zones.

Key words: AMMI, Correlation, Fonio, GGE, Path analysis, Stability, Yield.

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INTRODUCTION

Fonio (*Digitaria iburua Kippis* Stapf), commonly known as acha in Nigeria, is a cereal categorized among the diverse group of millets and predominantly grown across Africa. Fonio likely originated in West Africa (Morales, 2003), though archaeological evidence is scarce (Hilu et al., 1997). Cultivation may date back to 5000 BC, potentially making it the oldest African cereal (Pulseglove, 1972). From Cape Verde to the Chad basin, fonio thrives in diverse sandy, rocky, and loamy soils, tolerating both drought and flood conditions (Abdullahi and Luka, 2003; Morales, 2003). Fonio serves as a staple food in fifteen North West African countries (Jideani, 1999), supporting low-input farming systems, particularly for resource-poor farmers.

While Philip and Itodo (2006) identified over 300 species within the genus, CIRAD (2004) reported only three or four as being cultivated. However, Isong *et al.* (2022) documented two cultivated species in Nigeria: *D. iburura* and *D. exilis*. *Digitaria iburua* is an herbaceous plant with an erect growth habit, drooping leaves, and a height of up to 150cm, maturing approximately 140 days after planting. Despite its potential, fonio production remains low, accounting for less than 1% of the national cereal harvest, with grain yield ranging from 200 to 700 kg/ha (Dachi *et al.,* 2017). Research efforts to improve fonio yield have been minimal. Additionally, climate change poses a significant challenge, prompting many farmers to abandon the crop in key growing areas. Developing improved varieties with higher yields, stability, and adaptability to diverse environmental conditions could significantly enhance fonio productivity in the region.

The performance of fonio genotypes across varying environments depends on genotype-environment interactions. According to Fikere *et al*. (2014), the crop environment encompasses external factors beyond the genetic makeup of the genotype or variety. Gauch (2006) emphasized that improving crop performance by ranking genotypes across environments would aid in selecting and recommending genotypes for specific environmental adaptations. With climate change severely impacting agricultural productivity, sustainability in agricultural systems has become a priority (Kang and Banga, 2013). Genotype stability and adaptability are considered critical traits by researchers (Muzari *et al*., 2012; Lobell, 2009) for achieving food security in Sub-Saharan Africa.

Analysis for Genotype×Environment Interaction (GEI), as well as the stability and adaptability of genotypes, often involve tools such as GGE biplots (Singh *et al.,* 2014) and the Additive Main Effects and Multiplicative Interaction (AMMI) model. While GGE biplots enable the simultaneous analysis of multiple genotypes and environments, the AMMI model combines Analysis of Variance (ANOVA) with Principal Component analysis (PCA) to partition variance. Isong *et al*. (2022) suggested that using both methods together can help identify the best-performing, stable, and representative genotypes suited to specific environmental conditions.

Similarly, grain yield, which is a product of the interaction between various contributing traits, is highly sensitive to environmental variations (Vernier and Dansi, 2000; Obiokoro, 2005). The relationship between yield and its contributing traits can be either direct or indirect. Isong *et al*. (2013) emphasized that understanding the direct and indirect interactions of contributing traits with yield is crucial for determining the significance of each characteristic. The number of characters associated with yield may be extensive, making the interactions increasingly complex. Correlation coefficients can effectively determine the relationships among these associated characters, providing a foundation for efficient selection based on phenotypic or genotypic interactions. Liaqat *et al*. (2015) and Iqbal *et al*. (2006) emphasized that path coefficient analysis is essential for effective selection and trait improvement, as it uncovers the relationships among yield-contributing traits. Similarly, Isong *et al.* (2017) recommended the use of path analysis when dealing with multiple traits and complex interactions.

This study aimed to examine the relationship between fonio grain yield and its contributing traits, dissect this relationship into direct and indirect effects, and identify key components for selection. Additionally, it sought to determine and recommend the most stable and adaptable genotypes across various locations to enhance production.

MATERIAL AND METHODS

Experimental location

This study aimed to analyze the traits associated with fonio grain yield and stability during the 2022 and 2023 growing seasons (June-November). Nursery and field activities took place at the National Cereals Research Institute's experimental fields in Badeggi and eight other out-stations across the country (Amakama, Bacita, Mokwa, Ibadan, Warri, Imane, Ryom, Kebbi) as detailed in Table 1.

Table 1. Agroecology and coordinates of nine experimental sites in Nigeria selected to assess the sustainability and adaptability of fonio (*Digitaria iburua Kippis* Stapf) populations during the 2022 and 2023 growing seasons.

Site	Sub-national	Agro-Ecology	Longitude	Latitude	Elevation (masl)	Rainfall (mm)	Mean Tempt. (^{o}C)
Amakama	Abia	Humid Rainforest	007^{o}28.373^{I}	05^{o}27.282^{I}	132	144.35	27
Bacita	Niger	Southern Guinea Savanna	004^{o}95.852'	09^{o}07.063^{I}	150	125.14	28
Badeggi	Niger	Southern Guinea Savanna	006^{o}14.342^{I}	09^{o}05.683^{I}	118	124.32	32.09
Birnin Kebbi	Kebbi	Sudan Savanna	005^{o}19.673^{I}	11^{o}26.142'	259	83.3	28
Ibadan	Oyo	Derived Guinea Savanna	003o91.194^{I}	07^{o}40.566^{I}	230	125	26
Imane	Koggi	Derived Guinea Savanna	007^{o}69.999^{I}	07^{o}28.333^{I}	425	167	27
Mokwa	Niger	Southern Guinea Savanna	5.0546643^{I}	9.2928243^{I}	335	100	27
Ryom	Plateau	Northern Guinea savanna	008'45.499'	09'38.220'	1,210	100	23
Warri	Delta	Mangrove swam forest	005^{o}46.922^{I}	05^{o}3130^{I}	5	250	27

Experimental Materials and Experimentation

Genetic material consisted of twelve selected lines from the NCRI gene bank and a check variety. Experiments at all locations followed a Randomized Complete Block Design with three replicates and a plot size of 3m×4m. Seedlings, raised in a nursery, were transplanted 30 days after planting, with two vigorous seedlings per stand at a spacing of 20cm×20cm. Standard cultural practices were implemented, including soil conditioning, fertilizer application, weeding, pest control, and bird scaring. A 15:15:15 NPK inorganic fertilizer was applied in two splits of 30 kg N/ha, 30 kg P_2O_2, and 30 kg/ha K_2O at 4 and 8 weeks after planting (WAP). Bird scaring was conducted from panicle initiation until harvest, and manual weeding was performed three times before harvest.

Observation, Data collection, and statistical analysis

Data were collected on various traits, including days to 50% flowering, number of tillers per plant, number of panicles per plant, plant height (cm), spike length (cm), panicle length (cm), number of spikes per plant, days to maturity, and grain yield (kg/ha). Combined analysis of variance (ANOVA) was performed using Statistical Tools for Agricultural Research (STAR, 2014), and means were separated using the Least Significant Difference (LSD). Associations were assessed via correlations and path analysis using Dewey and Lu's method (1959) with AGRISTAT statistical software. Genotype stability and ideal environments were determined through AMMI and GGE Biplot analyses using the Plant Breeding Tools (PBTools, 2013).

RESULTS AND DISCUSSION

The agro-ecological characteristics and coordinates of the nine experimental sites in Nigeria are summarized in Table 1. Descriptive statistics, *per se* performance, and analysis of variance results are detailed in Table 2. Genotypic and phenotypic correlation among 13 Fonio pure lines are presented in Table 3, while regression analysis and direct path coefficients are provided in Table 4. Additionally, the combined yield performance of *D. iburua* pure lines across nine locations over two years, along with the Finlay-Wilkinson stability model and AMMI analysis, and GGE analysis of nine principal components, are illustrated in Tables 5, 6, 7, and 8, respectively.

Table 2 highlights significant variability in the population, as the genotypes for all studied parameters showed significant differences at the 0.05 probability level. Umar *et al*. (2020) suggested that such variability offers breeders better opportunities to enhance traits through selection and recombination. Genotype IBPL05-19-03 achieved the highest yield of 1113.89 kg/ha was recorded for and also recorded the highest number of spikes per plant (7.64). The variation in days to 50% flowering ranged from 108.91 to 121.62 days, suggesting that certain genotypes are better suited for early-maturing conditions, while others are adapted to longer growing seasons. Yan *et al*. (2021)

noted that early-flowering varieties are beneficial in regions with shorter rainy seasons, as they complete their growth cycle before dry spells, thereby increasing yield potential. Shavrukov *et al*. (2017) suggested that under drought conditions, early maturation enables plants to complete the reproductive phase before water stress becomes critical. IBPL02-10-11 was the earliest maturing genotype, reaching maturity in 131.5 days. However, its grain yield averaged 746.67 kg/ha across nine locations over two years, which is below the mean grain yield of all genotypes recorded at 799.27 kg/ha. The mean plant height was 122.84 cm, ranging from 102.98 cm to 140.31 cm, while the mean spike length was 13.83 cm with a range of 10.68 cm to 16.42 cm across all genotypes. Wang *et al*. (2023) demonstrated that taller plants are associated with higher photosynthetic areas and better yields, though they are more prone to lodging. Similarly, Janmohammadi *et al.* (2019) identified a positive correlation between spike length and grain yield in wheat, suggesting that longer spikes often lead to more grains per spike, enhancing overall yield.

The population's mean grain yield was 799.27 kg/ha with a wide variability ranging from 562.44 kg/ha to 1122.89 kg/ha, indicating significant differences in agronomic performance among genotypes. Katsenios et al. (2021) in their study on maize, demonstrated that grain yield varies substantially across varieties due to differences in genotype, environmental conditions, and management practices. Rehman *et al*. (2021) further established that varieties with greater resistance to biotic and abiotic stresses tend to exhibit higher yield potentials.

The mean days to maturity across genotypes was 137.46 days. Makinde *et al*. (2023) similarly highlighted a trade-off between early maturity and grain yield, emphasizing that while early-maturing crops are advantageous in regions with short growing seasons, they may not achieve the highest yields compared to longer-maturing varieties. Therefore, genotypes with moderate maturity periods often strike a balance between yield and resilience, especially under variable climatic conditions (Bassi and Nachit, 2019).

In Table 3, the phenotypic and genotypic correlation coefficients illustrate the relationships between various agronomic traits in the fonio plants, measuring both the strength and direction of these associations. For example, days to 50% flowering exhibited a strong positive phenotypic correlation with grain yield (0.895), indicating that later-flowering genotypes tend to produce higher yields. Similarly, the genotypic correlation was even higher, showing a similarly high value (0.969), indicating a robust genetic link between days to 50% flowering and grain yield. These findings align with Gonçalves *et al*. (2021), who highlighted that late-flowering varieties accumulate more biomass and achieve higher yields under optimal conditions.

The number of tillers per plant also showed a strong positive phenotypic correlation with grain yield (0.879), implying that an increase in tillers improves yield potential. This trend is well-documented in cereals, where more tillers result in more productive spikes and grains. The genotypic correlation for this trait was exceptionally high (0.98), emphasizing that the relationship is predominantly genetic, which is advantageous for breeding programs aimed at enhancing tillering ability. Similar conclusions were drawn by Fischer (2014) and Mishra *et al*. (2019), who observed that increased tillering contributes significantly to higher grain yields.

Furthermore, the number of panicles per plant showed a very strong positive phenotypic correlation with grain yield (0.977), and an equally strong genotypic correlation (0.981), suggesting that this trait is largely governed by genetic factors. These findings are supported by Krishnamurthy *et al*. (2014), who emphasized the critical role of the number of panicles per plant in reproductive success and yield potential in cereals.

Other traits, such as plant height, spike length, panicle length, and the number of spikes per plant, also showed positive phenotypic and genotypic correlations with grain yield. This suggests that taller plants with more and longer spikes generally produce higher grain yield. Researchers like Zhao *et al*. (2021), Teng *et al*. (2022), and Qin *et al*. (2023) have reported similar observations in their studies on rice, maize, and barley, respectively. These findings collectively underscore the genetic basis of these traits and their importance in improving grain yield through targeted breeding efforts.

Path coefficient analysis results are detailed in Table 4, which partitions the total relationship between two variables into direct and indirect effects. The direct path coefficient quantifies the impact of a predictor trait on grain yield, while the indirect path coefficient evaluates the influence mediated through other variables. Path coefficients range from -1 to +1, with higher values signifying stronger relationships. Positive direct path coefficients indicate that an increase in the independent trait corresponds to an increase in grain yield, whereas negative coefficients indicate the opposite. Indirect

Table 2. Grain yields for 2022 and 2023, along with data on yield-related traits in fonio (*Digitaria iburua Kippis* Stapf) lines cultivated across nine regions in Nigeria.

Genotypes	Pedigree	DFF	NTPP	NPPP	PH	SL	PL	NSPP	DM	GY		
										2022	2023	Mean
IBPL02-12-01	Nasnelleng	118.8	27.4	27.1	137.2	15.8	23.8	7.4	138.4	986.8	993.3	990.1
IBPL02-04-02	Nibang	119.1	21.4	20.2	140.3	14.7	22.5	7.2	139.7	864.4	926.8	895.6
IBPL05-19-03	Jakalak	110.7	26.0	21.9	134.7	14.9	23.5	7.6	132.7	1122.9	1104.9	1113.9
IBPL04-06-04	Dampep	115.5	21.4	20.6	139.9	13.6	21.0	6.3	135.0	679.4	704.4	691.9
IBPL04-18-05	Dinat	121.6	25.9	19.4	114.8	16.4	22.3	7.2	142.5	784.3	758.9	771.6
IBPL02-11-06	Sunpiya	108.9	21.3	19.9	102.9	11.5	15.5	6.2	132.9	840.0	740.1	790.1
IBPL01-13-07	Gotip	111.4	21.9	21.2	108.5	13.6	25.1	6.5	135.3	708.8	679.2	694.0
IBPL04-15-08	Danto	115.3	21.4	20.1	120.2	13.8	18.4	7.1	137.1	687.9	726.9	707.4
IBPL05-07-09	Dipiya	114.8	18.9	20.4	113.5	10.7	25.7	5.3	136.2	729.8	781.9	755.8
IBPL03-02-10	Ganawuri	118.9	21.3	20.6	106.8	13.3	17.3	6.2	142.9	816.1	772.3	794.2
IBPL02-10-11	Jarab	109.4	21.4	30.0	121.3	13.3	25.5	6.2	131.5	773.7	719.7	746.7
IBPL01-17-12	Akwa acha	119.5	20.8	20.5	132.8	14.5	21.0	7.2	142.4	806.8	844.6	825.7
Local check	Iburu	118.6	20.05	20.9	123.9	13.7	22.9	6.2	140.5	562.4	664.6	613.5
Mean		115.6	22.2	21.8	122.8	13.8	21.9	6.7	137.5	797.2	801.4	799.3
Max		121.6	27.4	30.0	140.3	16.4	25.7	7.6	142.9	1122.9	1104.9	1113.9
Min		108.9	18.9	19.4	102.9	10.7	15.5	5.3	131.5	562.4	664.6	613.5
SE		2.0	0.4	0.4	2.7	0.3	0.4	0.1	2.7	4.9	5.4	3.2
Coefficient of variation (%)		3.0	11.4	14.4	10.6	11.2	14.5	10.0	2.9	17.8	16.5	16.8
LSD		7.5	1.6	1.4	9.9	1.1	1.4	0.5	9.8	17.9	19.6	11.8

DFF: Days to 50% flowering, NTPP: Number of tillers per plant, NPPP: Number of panicles per plant, PH: Plant height (cm), SL: Spike length (cm), PL: Panicle length (cm), NSPP: Number of spikes per plant, DM: Days to maturity, GY: Grain yield (kg/ha). Local check – popular farmers' variety.

Table 3. Genotypic and phenotypic correlations between important agronomic traits studied in 13 fonio lines (*Digitaria iburua Kippis* Stapf).

		DFF	NTPP	NPPP	PH	SL	PL	NSPP	DM	GY (kg/ha)
DFF	p	1.00	0.95**	0.93**	0.88**	0.87**	0.89**	0.88**	0.87**	0.90**
	g	1.00	0.98**	0.99**	0.94**	0.94**	0.96**	0.95**	0.93**	0.97**
NTPP	p		1.00	0.88**	0.87**	0.86**	0.89**	0.86**	0.85**	0.88**
	g		1.00	0.99**	0.99**	0.98**	0.99**	0.99**	0.97**	0.99**
NPPP	p			1.00	0.97**	0.98**	0.97**	0.97**	0.95**	0.98**
	g			1.00	0.98**	0.98**	0.98**	0.98**	0.96**	0.98**
PH	p				1.00	0.98**	0.97**	0.99**	0.94**	0.99**
	g				1.00	0.98**	0.97**	0.99**	0.95**	0.99**
SL	p					1.00	0.97**	0.97**	0.96**	0.97**
	g					1.00	0.97**	0.97**	0.96**	0.97**
PL	p						1.00	0.97**	0.95**	0.98**
	g						1.00	0.97**	0.95**	0.98**
NSPP	p							1.00	0.94**	0.99**
	g							1.00	0.94**	0.99**
DM	p								1.00	0.94**
	g								1.00	0.94**
GY (kg/ha)	p									1.00
	g									1.00

DFF: Days to 50% flowering, NTPP: Number of tillers per plant, NPPP: Number of panicles per plant, PH: Plant height (cm), SL: Spike length (cm), PL: Panicle length (cm), NSPP: Number of spikes per plant, DM: Days to maturity, GY: Grain yield (kg/ha). Local check – popular farmers' variety.

*: P≤0.05, **: P≤0.01.

p: Phenotypic correlation, g: Genotypic correlation.

path coefficients reveal how a trait affects the grain yield indirectly via other traits.

According to the scale proposed by Lenka and Mishra, (1973), the indirect path for days to 50% flowering through panicle length (0.446), plant height (0.734) and number of panicles per plant (0.587) were high and positive, while the path through the number of spikes per plant was positive but negligible in its impact on grain yield. Direct effects of panicle length (0.466), plant height (0.780), and number of panicles per plant (0.589) were also observed to be positive and significant. Conversely, spike length exhibited high but negative direct effects (-0.495), while days to 50% flowering and number of tillers per plant showed low and negative direct effects (-0.123 and -0.124, respectively). The results are consistent with previous studies by Hossain *et al*. (2020), Niu *et al.* (2021), and Wu and Ma (2022), which warned that excessive plant height in *D. iburua* fonio, driven by enhanced photosynthesis potential and its strong positive correlation with grain yield, may become disadvantageous if it results in lodging. Khobra *et al* (2019) further explained the trade-off between plant height and lodging, highlighting that plant height is a reliable predictor of lodging due to its impact on the center of gravity and mechanical leverage on the stem and roots, making plants more susceptible to wind or rain-induced lodging. Additionally, the result revealed that the number of tillers per plant had a low and negative influence on grain yield. This contrasts with the findings of Mishra *et al.* (2019) but aligns with Laxmi *et al.* (2021), who suggested that tiller number indirectly affects grain yield through its influence on the number of panicles, plant height, and panicle length.

Analysis of two-year yield data from nine locations (Table 5) provides insights into genotype-environment interactions. Line IBPL05-19-03 showed consistently high yields, indicating broad adaptability. This aligns with findings from other fonio studies showing significant genotype-environment interactions, where location-specific adaptation and environmental factors greatly influence grain yield (Magar *et al.*, 2024; Kebede *et al.*, 2019). These results support Ndeko *et al.* (2022)

Table 4. Direct and indirect effects of some important predictive traits on fonio (*Digitaria iburua Kippis* Stapf) grain yield.

	DFF	NTPP	NPPP	PH	SL	PL	NSPP	DM	GY (kg/ha)
DFF	**-0.123**	-0.121	0.587	0.734	-0.464	0.446	0.010	-0.100	0.969
NTPP	-0.120	**-0.124**	0.592	0.770	-0.484	0.472	0.010	-0.104	1.013
NPPP	-0.122	-0.124	**0.589**	0.760	-0.485	0.455	0.010	-0.102	0.981
PH	-0.116	-0.122	0.574	**0.780**	-0.487	0.452	0.010	-0.101	0.991
SL	-0.115	-0.121	0.577	0.766	**-0.495**	0.454	0.010	-0.102	0.974
PL	-0.117	-0.125	0.575	0.755	-0.482	**0.466**	0.010	-0.102	0.980
NSPP	-0.117	-0.122	0.576	0.773	-0.480	0.454	**0.010**	-0.101	0.993
DM	-0.115	-0.120	0.563	0.737	-0.473	0.445	0.010	**-0.107**	0.940

DFF: Days to 50% flowering, NTPP: Number of tillers per plant, NPPP: Number of panicles per plant, PH: Plant height (cm), SL: Spike length (cm), PL: Panicle length (cm), NSPP: Number of spikes per plant, DM: Days to maturity, GY: Grain yield (kg/ha). Local check – popular farmers' variety.

Table 5. Combined yield of fonio (*Digitaria iburua Kippis* Stapf) lines studied in 9 selected locations in Nigeria during the 2022 and 2023 growing seasons.

Genotypes	Amakama	Bacita	Mokwa	Ibadan	Warri	Imane	Riyom	Kebbi	Badeggi
IBPL02-12-01	1029.0	905.5	968.5	1189.5	884.0	844.0	1065.0	850.5	1147.0
IBPL02-04-02	716.0	1145.0	707.0	819.0	805.0	1203.5	946.5	854.0	1069.5
IBPL05-19-03	809.0	969.5	1373.0	877.0	1118.5	983.0	1464.5	954.5	1404.0
IBPL04-06-04	625.5	672.0	774.0	692.0	750.0	623.5	756.0	634.0	678.5
IBPL04-18-05	722.0	801.5	752.0	804.5	765.5	627.5	777.0	784.0	834.5
IBPL02-11-06	702.0	610.5	839.0	784.0	1170.0	622.0	678.5	708.0	705.0
IBPL01-13-07	686.0	658.5	673.5	594.0	665.5	764.0	759.5	754.5	770.5
IBPL04-15-08	663.0	702.0	653.0	695.5	716.5	611.0	784.0	622.5	898.0
IBPL05-07-09	665.0	825.0	850.5	741.5	689.0	706.5	791.0	687.5	860.0
IBPL03-02-10	755.0	775.5	905.0	857.5	832.5	756.5	789.0	676.0	773.0
IBPL02-10-11	732.0	783.0	770.0	746.0	756.0	630.0	815.0	683.0	767.0
IBPL01-17-12	839.0	765.0	833.5	793.5	832.5	739.0	790.0	1111.0	711.0
Check	527.5	639.0	678.5	619.5	596.5	680.0	603.5	598.0	616.5
Mean	728.54	788.62	829.04	785.65	813.96	753.12	847.65	762.88	864.19
Max	1029.0	1145.0	1373.0	1189.5	1170.0	1203.5	1464.5	1111.0	1404.0
Min	527.5	610.5	653.0	594.0	596.5	611.0	603.5	598.0	616.5
SE	11.6	11.4	11.6	10.3	12.7	11.9	11.7	12.2	11.5
Coefficient of variation (%)	11.6	16.5	19.5	12.5	18.7	20.4	20.3	17.3	19.3
LSD	42.35	41.69	42.36	37.67	46.41	43.55	42.87	44.70	42.20

suggestion that genotype selection for soil fertility is essential for high yield across diverse locations. Genotypes IBPL04-06-04 recorded relatively lower yields, relating to their potential for less adaptability to diverse agro-climatic conditions. Broadly adaptable genotypes like IBPL05-19-03 are suitable for regions with varied environmental conditions, while less adaptable genotypes like IBPL04-06-04 are better suited for specific micro-environments.

According to the model developed by Finlay and Wilkinson (1963), presented in Table 6, genotypes IBPL02-12-01, IBPL04-15-08, IBPL05-19-03, IBPL02-04-02, and IBPL05-07-09 exhibited slopes close to 1 (I.15, 0.96, 0.84, 0.63, and 0.76, respectively). This indicates their stability and general adaptability across diverse environments, aligning with the findings of Becker and Léon (1988), who emphasized that stable genotypes perform reliably in both high- and low-yielding conditions. Similarly, Lin *et al*. (1986) highlighted that genotypes with slopes near 1 can effectively buffer against environmental fluctuations, making them ideal for regions with variable climates.

In contrast, genotypes IBPL01-13-07 and IBPL01-17-12 demonstrated slopes greater than 1 (4.98 and 1.55, respectively), indicating a pronounced response to improved environmental conditions. Eberhart and Russell (1966) categorized such genotypes as suitable for high-input systems, where optimal conditions can maximize yield potential. A similar result was reported by Kang (1993), who noted that high-response genotypes are advantageous for exploiting favorable environments but require careful management in suboptimal areas.

Meanwhile, genotype IBPL04-06-04 exhibited a negative slope (-0.92), signifying poor stability. Ceccarelli (1996) explained that such slopes suggest suitability for marginal or low-input systems where environmental stressors are prevalent. Consequently, IBPL01-13-07 demonstrated a higher mean square (MS) for regression compared to deviation, indicating substantial genotype-by-environment (G×E) interaction and minimizing random errors in performance variability. This supports Crossa's (1990) findings. Conversely, genotype IBPL02-10-11 had lower MS regression values, reflecting minimal G×E interaction. According to Yan and Kang (2002), such genotypes are ideal for consistent but low-performing environments.

Significant t-values in genotype IBPL01-13-07 and check validate the slope behavior pattern, consistent with the findings of Gauch and Zobel (1997). On the other hand, the non-significant results for IBPL02-10-11 suggest the need for further evaluation, as the observed pattern might be attributed to randomness rather than environmental factors. In addition, the results in Table 6 also indicated that IBPL02-12-01 was broadly adaptable, corroborating Becker and Léon's (1988) perspective. The high responsiveness of genotypes IBPL01-13-07 supports Annicchiarico's (1997) recommendation for its use in high-input agriculture systems, where maximizing yield under favorable conditions is crucial.

According to the AMMI Analysis presented in Table 7, the first principal component (PC1) accounts for 34.7% of the total variance, while the second principal

Table 6. Finley and Wilkinson's sustainability model applied to the yield analysis of 13 fonio (*Digitaria iburua Kippis* Stapf) lines evaluated across 9 selected regions in Nigeria during the 2022 and 2023 growing seasons.

Genotype	Slope	Standard error	T value	Probability	MS regression	MS deviation
IBPL02-12-01	1.15	0.98	1.17	0.28	21600.75	15646.89
IBPL02-04-02	0.63	0.50	1.26	0.25	6509.29	4130.09
IBPL05-19-03	0.84	0.34	2.47	0.04	11524.04	1890.03
IBPL04-06-04	-0.92	0.91	-1.02	0.34	13952.88	13480.66
IBPL04-18-05	0.29	0.37	0.77	0.47	1350.95	2265.79
IBPL02-11-06	0.35	1.53	0.23	0.83	1949.84	38120.51
IBPL01-13-07	4.98	0.83	5.98	0.00	406654.59	11354.33
IBPL04-15-08	0.96	0.33	2.93	0.02	14965.99	1746.07
IBPL05-07-09	0.76	0.41	1.84	0.11	9463.05	2808.42
IBPL03-02-10	0.88	1.38	0.64	0.54	12745.95	31321.65
IBPL02-10-11	0.25	0.51	0.50	0.63	1055.14	4213.32
IBPL01-17-12	1.55	0.46	3.38	0.01	39555.33	3468.06
Check	1.28	0.41	3.15	0.02	26878.24	2708.68

Table 7. The analysis results of the nine principal components of AMMI derived from the performance stability study of 13 fonio (*Digitaria iburua Kippis* Stapf) lines evaluated across nine selected regions in Nigeria during the 2022 and 2023 growing seasons.

	AMMI Analysis						
	%	Acum	Df	SS	MS	F value	Pr F
PC1	34.7	34.7	19	1338331	70438	165.9	0
PC2	31.8	66.5	17	1228050	72238	170.2	0
PC3	14.5	81	15	559537	37303	87.9	0
PC4	10.6	91.6	13	410373	31567	74.4	0
PC5	4.7	96.3	11	183225	16657	39.2	0
PC6	2.2	98.5	9	85914	9546	22.5	0
PC7	0.9	99.4	7	36077	5154	12.1	0
PC8	0.5	99.9	5	20907.1	4181	9.9	0
PC9	0	99.9	3	0	0	0	1

Table 8. The analysis results of the nine principal components of GGE derived from the performance stability study of 13 fonio (*Digitaria iburua Kippis* Stapf) lines evaluated across nine selected regions in Nigeria during the 2022 and 2023 growing seasons.

	GGE Analysis						
	%	Acum	Df	SS	MS	F value	Pr F
PC1	66.1	66.1	19	6395723	336617	793	0
PC2	13.1	79.2	17	1270063	74709	176	0
PC3	7.9	87.1	15	766555	51104	120	0
PC4	5.6	92.7	13	546221	42017	99	0
PC5	4.1	96.8	11	397162	36106	85	0
PC6	1.8	98.6	9	171422	19047	45	0
PC7	0.9	99.5	7	84098	12014	28	0
PC8	0.3	99.8	5	31457	6291	15	0
PC9	0.1	99.9	3	12036	4012	10	0

component (PC2) contributes an additional 31.8%. Together, these two components explain a cumulative variance of 66.5%, effectively capturing the major patterns of genotype-by-environment interaction. This finding aligns with Gauch and Zobel (1996), who noted that PC1 and PC2 in AMMI analyses typically represent the most significant and meaningful interaction effects. Furthermore, Gauch (2006) highlighted that higher-order principal components often correspond to minor interaction effects or random noise, which may hold limited practical value for genotype selection and decision-making processes.

Genotype Plus Genotype-by-Environment Interaction (GGE) analysis in Table 8 simplifies genotype selection by emphasizing the "which-won-where" pattern and stability, making it more practical for breeders seeking actionable insights (Yan, 2013). In GGE analysis, PC1 explains 66.1% of the variance, much higher than AMMI's PC1, indicating GGE's focus on genotype main effects and GEI as the primary emphasis. Yan *et al.* (2000) previously advocated that GGE prioritizes genotype-centered variability. When PC2 variance (13.1%) is combined with PC1, the total variance reaches 79.2%, supporting Yan and Tinker's (2006) assertion that the first 2 principal components are typically sufficient for meaningful interpretation of genotype performance. Similar explanations derived from AMMI and GGE analyses are visually presented in Figures 1, 2, and 3.

The GGE biplot in Figure 1 illustrates strong stability and responsiveness for genotypes G1 and G3. Also, genotypes G1, G2, and G3 recorded yields above the average genotype mean. Figure 2 displays the "Which-Won-Where" Biplot for yield performance. While Genotype G1 exhibited better adaptation at locations E6, E4, and E1, Genotype G3 performed best in those locations as well as in E8, E3, and showed relative adaptation in E9 and E7. Genotype G2, however, performed optimally at location E2 (Bacita) and E5 (Imane), as shown in Figure 2.

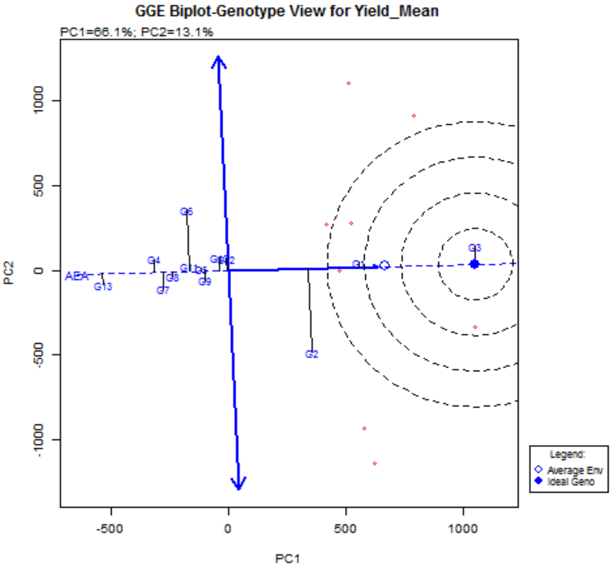


Figure 1. Mean vs. Stability view of GGE biplot showing the mean performance and stability of 13 fonio (*Digitaria iburua Kippis* Stapf) lines studied across nine selected regions in Nigeria during the 2022 and 2023 growing seasons.

Figure 3 evaluates the similarity, representativeness, and discriminating ability of the locations. The locations are grouped, showing similar environmental conditions during the trials. Locations E3 (Badeggi), E8 (Riyom), and E7 (Mokwa) had the longest projections, showing the highest discriminating ability. Representativeness of the locations is shown by their proximity to the Average Environment Axis

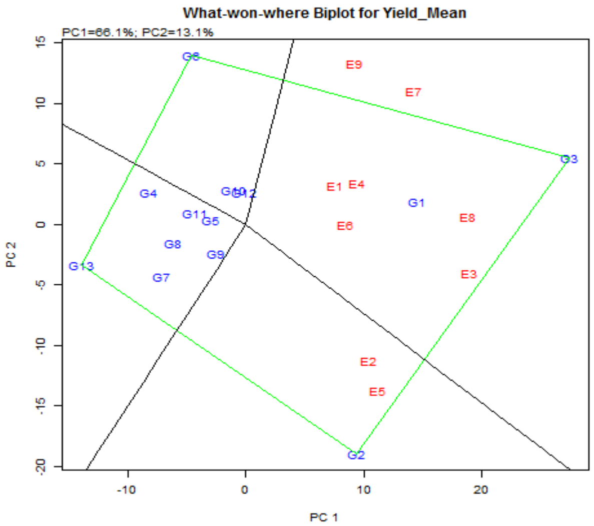
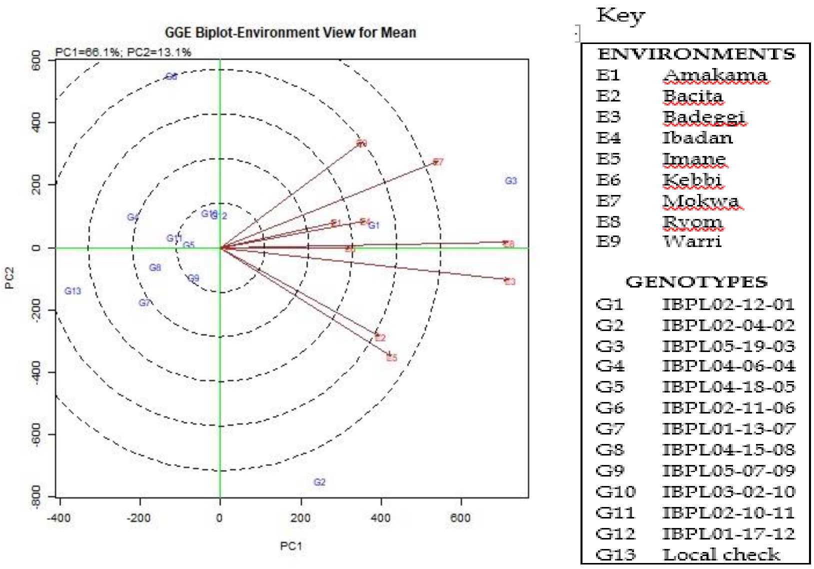


Figure 2. The which-won-where view of the GGE biplot, displaying the best performing fonio (*Digitaria iburua Kippis* Stapf) lines studied across nine selected regions in Nigeria during the 2022 and 2023 growing seasons.



ENVIRONMENTS	
E1	Amakama
E2	Bacita
E3	Badeggi
E4	Ibadan
E5	Imane
E6	Kebbi
E7	Mokwa
E8	Ryom
E9	Warri

GENOTYPES	
G1	IBPL02-12-01
G2	IBPL02-04-02
G3	IBPL05-19-03
G4	IBPL04-06-04
G5	IBPL04-18-05
G6	IBPL02-11-06
G7	IBPL01-13-07
G8	IBPL04-15-08
G9	IBPL05-07-09
G10	IBPL03-02-10
G11	IBPL02-10-11
G12	IBPL01-17-12
G13	Local check

Figure 3. GGE Biplot-Environmental view showing the similarity, representativeness, and discriminating ability of the locations. Locations E3, E8, and E7 show the highest discriminating ability with their longest projections.

(AEA). Locations E8 (Riyom) and E6 (Kebbi) were the most representative. Location E8 showed both high discriminating ability and strong representativeness, suggesting it should be prioritized in future evaluation for optimal performance.

CONCLUSION

Sufficient variability was observed within the population, with significant and large variation in grain yield linked to the agronomic performance of the genotypes. Plant height, spike length and panicle length, and number of spikes per plant showed positive phenotypic and genotypic correlations with grain yield, indicating strong genetic determination. The results from this study suggested that taller plants with longer and more spikes generally yield higher grain production. Genotype IBPL05-19-03 consistently delivered high yields across the locations, indicating its broad environmental adaptability and potential for advancement in regions with varying conditions. In contrast, less adaptable genotypes like IBPL04-06-04 are recommended for specific micro-environments. Genotypes IBPL02-12-01, IBPL04-15-08, IBPL05-

19-03, IBPL02-04-02, and IBPL05-07-09 exhibited slopes close to 1, indicating stability and general adaptability across different environments. Among these, genotypes IBPL05-19-03 and IBPL02-12-01, with their superior yields and favorable growth traits, should undergo further evaluation and promotion in regions with optimal conditions. Breeding efforts targeting improvements in plant height, panicle length, and the production of more tillers are likely to result in significant yield enhancements in fonio. Analytical approaches such as AMMI and GGE provide valuable tools for assessing the performance of fonio lines in multi-locational trials. AMMI offers detailed insights into the genotype-environment interaction effects, while GGE simplifies genotype selection by focusing on actionable patterns. Integrating these models into fonio population analysis ensures balanced statistical outcomes and informed decision-making, thereby supporting the development of high-yielding and stable genotypes across diverse environments.

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