



**STABILITY AND EVALUATION OF SOME CLIMATE-SMART SOYBEAN
(*Glycine max* Linnaeus Merrill) GENOTYPES IN NIGERIA**

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ABSTRACT

The study evaluated the performance, stability, and adaptability of twenty soybean genotypes across five contrasting environments (Badeggi, Amakama, Numan, Yandev, and Makurdi) to identify climate-smart, high-yielding, and stable varieties suitable for large-scale production. The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications. Data were collected on plant height, pods per plant, pod clearance and seed yield. Results of the study showed highly significant ($p \leq 0.01$) genotype, environment, and genotype \times environment interaction (GEI) effects for most traits. The Additive Main Effects and Multiplicative Interaction (AMMI) analysis identified genotypes G12 (TGx_24_40NG-0088) and G16 (TGx_24_43NG-0126) as the highest-yielding, with large IPCA values. Genotypes G6 (TGx_24_9NG-0025), G7 (TGx_24_13NG-0031), G8 (TGx_24_15NG-0034), G9 (TGx_24_17NG-0039), and G18 (TGx 1904-6F) recorded low IPCA1 scores. The environments (Badeggi, Amakama, Yandev, and Makurdi) formed one mega-environment, while Numan emerged as a distinct second mega-environment. Overall, the study successfully identified both high-yielding and stable soybean genotypes suitable for Nigeria's diverse Agro-ecologies. Genotypes G6 (TGx_24_9NG-0025), G7 (TGx_24_13NG-0031), G8 (TGx_24_15NG-0034), G9 (TGx_24_17NG-0039), and G18 (TGx 1904-6F) are recommended for wide adaptation, while G12 (TGx_24_40NG-0088) and G16 (TGx_24_43NG-0126) are ideal for high-potential environments. These findings provide essential information for soybean improvement, climate-smart agricultural planning, and national varietal release.

Keywords: Adaptability, Climate-smart, Mega-environment, Stability, Variability

INTRODUCTION

Soybean (*Glycine max* Linnaeus Merrill) belongs to the family *Fabaceae*, sub-family Papilionoidae and is a globally significant annual leguminous crop. It provides 40% protein and 18–22% oil of which 85% is cholesterol free and contains 20 to 22% essential amino acids for human consumption, animal feed, and industrial applications (Kolesar *et al.*, 2020; Bozhanska and Naydenova, 2020). About 60% of the required nitrogen is obtained biologically by nodule bacteria (Fan *et al.*, 2019), and under optimal conditions it can fix up to 450 kg N/ha (Vasileva *et al.*, 2023). However, soybean productivity is highly influenced by environmental factors, including temperature fluctuations, rainfall variability, soil conditions, and other climatic changes significantly impact soybean growth, yield, and quality. Climate change is long-term alterations in temperature, precipitation, wind patterns, and other aspects of the Earth's climate system (NASA, 2023). Developing countries in Africa are more vulnerable to climate change and they lack the capacity to build resilience and adapt to climate change. Thus, the development and identification of climate-smart soybean genotypes that exhibit stability and adaptability across diverse environments have become crucial in ensuring sustainable production. The performance of soybean genotypes is determined by both genetic makeup (genotype) and environmental conditions, leading to a phenomenon known as genotype by environment interaction (GEI). According to Abate *et al.* (2015) the different responses of genotypes across environments is often normal in multi-environmental trials and it is known as genotype-environment interaction. GEI occurs when different



genotypes respond differently to varying environmental conditions, making it essential to assess and select genotypes that perform consistently well under diverse climatic conditions.

The increasing unpredictability of climatic conditions, including rising temperatures, droughts, and unpredictable rainfall patterns, poses a significant challenge to soybean production. The challenges that global warming poses to agriculture required that agricultural scientists develop response mechanisms to mitigate the changes in the environment. It has been established that genotypes that are stable across varied environments are better for breeding programme (Andrew *et al.*, 2014). Stability of yield of a cultivar across a range of production environments is very important for varietal recommendation. Therefore, it is of utmost importance to develop new high yielding genotypes that was stable and tolerant to both biotic and abiotic stresses, traits that add value to the product, and the stability of these traits in target environments will result to increase in yield. Thus, the study is to evaluate the stable climate-smart soybean genotypes under different environmental conditions with superior resilience to climate stress.

MATERIALS AND METHODS

Study Area

The experiment was conducted across five locations Badeggi (Niger State), Amakama-Olokoro (Abia State), Numan (Adamawa State), Yandev (Benue State) at National Cereals Research Institute Stations and Joseph Sarwuan Tarka University, Makurdi, during 2025 rainy season. The seeds of soybean genotypes were obtained from NCRI/IITA.

Treatments and Experimental Design

The treatment consisted of twenty soybean genotypes arranged in Randomized Complete Block Design with three replications across the locations. The plot size was 3m x 1.5m and 50 cm by 5 cm inter and intra row spacing for each treatment. The land was ploughed, and harrowed after two weeks.

Cultural Practices

Planting was carried out between mid-June to ending of June. Pre-emergence herbicide was applied using Butachlor (50 EC) at the rate of 2 litres per hectare was used in all the locations. Supplementary weeding was done at four and seven weeks after planting using hoe.

Single super phosphate (SSP) was applied by hand at the rate of 40 kg P₂O₅ /ha at 2 weeks after sowing, using side placement method of fertilizer application.

Cypermethrin (Best) at the rate of 0.14 kg a.i /ha (Tolorunse, 2017) was applied once on the seedlings with knapsack sprayer to control insect pests' infestation.

At physiological maturity (when the leaves turn brown and 95 % of the pods turn straw colour to brown), soybean plants were harvested from each net plot leaving the border rows on either ends of the central rows. The number of plants per net plot was recorded at harvesting from the three central rows, and the means computed and used for the analysis of final plant stands. The harvested net plots were threshed after taking the necessary parameters. The seeds were separated from the husk and kept in labelled bags representing respective plots for further observations (Tolorunse, 2017)

Data Collection

Observations were recorded on five plants, randomly selected from each genotype in all the three replications for Plant height at harvest/plant (cm) (length in cm of the main stem was taken from ground level to the apex (not petioles and leaves) at the time of maturity), Pods/plant (total numbers of pods of tagged plants were counted individually at the time of maturity to work out the pods per plants), Pod clearance (collection of the height of lowest pod data at harvest was by measuring height of the lowest pod to the ground level) and Seed yield/ (g) (seeds were uniformly dried before weighing in grams 3 m in the centre of the plot).

Data Analysis

All data collected were analyzed using BMS version: 1.9. 2015. Genotype was considered as fixed effect while locations as random effects. Analysis of variance was performed using the procedure outlined by Shaahu *et al.* (2014) for each of the parameters measured. interactions between genotypes and environments. The mean separation was performed using Duncan's Multiple Range Test (Tolorunse



et al., 2018). AMMI biplot and GGE biplot was used to determine which genotypes is most stable across test environment.

RESULTS

Table 1 shows the mean plant height at maturity which differed significantly ($P \leq 0.05$) across all tested locations. At Badeggi, plant height ranged from 33.45-51.80 cm with genotype TGx 2024-7E being the tallest and it differed significantly from other genotypes, TGx_24_11NG-0028 was the shortest at 33.45 cm which is not significantly different from TGx 1835-10E with 34.80 cm. At Amakama, genotype TGx_24_40NG-0091 attaining highest value for plant height at 70.07 cm. TGx_24_11NG-0028 was the shortest with a height of 38.07 cm. At Numan, TGx_24_15NG-0034 attaining the highest plant height of 83.63 cm and genotype. TGx_24_11NG-0028 recorded the lowest plant height of 38.07 cm. At Yandev location, TGx_24_40NG-0091 attaining the highest plant height which was significant from other genotypes. This result is in conformity with Kolesar *et al.* (2020) who reported that plant height is one of the most environmentally responsive growth components in soybean.

Table 1: Plant Height (cm) at Maturity Across Different Locations

Genotype		Badeggi	Amakama	Numan	Yandev	JSTU, Markudi
TGx_24_2NG-0003	G1	42.63def	64.77b	76.03b	64.77b	65.80bcd
TGx_24_2NG-0005	G2	47.40bc	63.70b	64.43d	63.70b	64.53cd
TGx_24_5NG-0011	G3	36.72ghi	50.13ghi	52.33f	50.13ghi	48.12fg
TGx_24_9NG-0023	G4	39.33fgh	63.00bc	64.37d	63.00bc	48.87fg
TGx_24_9NG-0024	G5	36.80ghi	45.03k	49.29f	45.03k	75.12a
TGx_24_9NG-0025	G6	37.24ghi	57.20de	64.90d	57.20de	48.92fg
TGx_24_13NG-0031	G7	48.34abc	59.27cd	78.23b	59.27cd	58.06e
TGx_24_15NG-0034	G8	50.55ab	64.97b	83.63a	64.97b	66.60bc
TGx_24_17NG-0039	G9	43.48de	52.70fgh	56.50e	52.70fgh	62.23d
TGx_24_27NG-0057	G10	37.18ghi	55.00ef	57.77e	55.00ef	58.03e
TGx_24_29NG-0061	G11	43.31de	47.03ijk	62.80d	47.03ijk	47.80fg
TGx_24_40NG-0088	G12	45.28cd	66.00b	57.13e	66.00b	68.17bc
TGx_24_40NG-0091	G13	40.17efg	70.07a	57.27e	70.07a	56.25e
TGx_24_42NG-0100	G14	35.78hi	45.17jk	56.87e	45.17jk	47.10g
TGx_24_43NG-0108	G15	41.43def	48.93hij	57.87e	48.93hij	69.57b
TGx_24_43NG-0126	G16	41.32ef	54.77ef	64.75d	54.77ef	51.07f
TGx_24_11NG-0028	G17	33.45i	38.07l	42.73g	38.07l	40.32h
TGx 1904-6F	G18	37.27ghi	53.33efg	62.77d	53.33efg	55.14e
TGx 2024-7E	G19	51.80a	54.16ef	61.76d	54.16ef	56.12e
TGx 1835-10E	G20	34.80i	55.03ef	70.77c	55.03ef	57.52e
SE±		0.79	0.14	0.41	0.11	0.14

Means followed by the same within the column are not significantly different at $p \leq 0.05$ from each other by Duncan Multiple Range Test, SE- Standard Error, JSTU- Joseph Sarwuan Tarka University, Markudi

Table 2 showed result of mean performance of Soybean genotypes for numbers of pod/plant across different locations. The result indicated that, in all the locations, numbers of pod/plant ranged from 21.04 to 65.81 pods per plant. Genotype TGx_24_43NG-0126 produced more number of pods which is significantly different from other genotypes except at Joseph Sarwuan Tarka University, Markudi were TGx_24_40NG-0091 produced more pods per plant than other genotypes. The result for pod number confirms earlier reports that reproductive traits in soybean are highly influenced by environmental fluctuations, particularly during flowering and pod-setting stages (Ngwu *et al.*, 2023).

Figure 1 presented the result of AMMI biplot for seed yield/plot (g) of Twenty Soybean genotypes (G) and five environments (E) using genotypic and environmental scores. Biplot are graphs



where aspects of both genotypes and environments are plotted on the same axes so that inter relationship can be visualized. In the AMMI 1 biplot, the visual interpretation of biplot is that the displacements along the abscissa indicate differences in mean (additive) effects, whereas displacements along the ordinate indicate differences in interaction effects. Genotypes G, G14, G8, G9, G7 and G11 that are group together have similar adaptation while environments E1 (Badeggi), E5 (Joseph Sarwuan Tarka University, Markudi), E4 (Yandev) and E2 (Amakama) which group together influences the genotypes in the same way. The best adapted genotype G5 (Joseph Sarwuan Tarka University, Markudi) was far from the environment. Genotype G8, G9 and G7 have a IPCA1 score of nearly zero, it has small interaction effects and considered as stable. Genotypes and environments on the same parallel line, ordinate have similar yields and a genotype or environment on the right side of the mid-point of this axis has higher yields than those of left-hand side. Consequently, among the genotypes G12 and G16 were generally seen with high seed yield with high main (additive) effects showing positive IPCA1 score, but not adapted to any environments. Similarly, Genotype G4, G19, G20 and G17 are low seed yield with showing negative IPCA1 score and adapted to no environments. Four environments: E1, (Badeggi), E2 Amakama, E4 (YAndev) and E5 (Joseph Sarwuan Tarka University, Markudi) were considered as the favourable environments for genotypes G6, G14, G2, and G7. The genotype G6 and G18 showed IPCA1 score close to zero, indicating that the genotype was stable and less influenced by the environments. Other genotypes showed low average seed yield. Similarly, the genotype G14 was moderately stable across environments (low positive IPCA1 score) and below average yield. This agrees with Kurasiak-Popowska et al. (2024), who reported that genotypes near the origin in AMMI biplots are ideal for cultivation across variable environments.

The AMMI 2 biplot for seed yield/plot (g) showing the interaction of IPCA2 against IPCA1 scores of 20 soybean genotypes (G) in five environments (E) is presented in *Figure 2*. In AMMI 2 biplot the environmental scores are joined to the origin by side lines. Site with short spokes do not exert strong interaction forces. Those with long spoke exert strong interaction. E1 (Badeggi), E2 (Amakama), E3 (Numan), E4 (Yandev) and E5 (Joseph Sarwuan Tarka University, Markudi) are connected to the origin. The environments E1 (Badeggi) had short spokes and do not exert strong interactive forces. The environments that exert the strongest interactive forces are E2 (Amakama), E3 (Numan), E4 (Yandev) and E5 (Joseph Sarwuan Tarka University, Markudi). The genotypes occurring close together on the plot will tend to have similar yields in all environments, while genotypes far apart may either differ in mean yield or show a different pattern of response over the environments. Hence, the genotypes near the origin are not sensitive to environmental interaction and those distant from the origin are sensitive and have large interaction. Genotypes G18, G4, G6 and G8 were close to the origin and hence they were sensitive to environmental interactive forces. According to Yan et al. (2021), such genotypes are critical for climate-smart agriculture because they reduce production risks under unpredictable climatic conditions.

Table 2: Number of Pod/plant Across Different Locations

Genotype	Badeggi	Amakama	Numan	Yandev	JSTU, Markudi
TGx_24_2NG-0003	29.50k	34.39j	29.57j	29.50k	34.39g
TGx_24_2NG-0005	42.06f	41.99e	42.06f	42.06f	42.06e
TGx_24_5NG-0011	51.83b	52.50b	51.83b	51.83b	29.87i
TGx_24_9NG-0023	23.81l	23.88k	23.81l	23.81l	29.63i
TGx_24_9NG-0024	21.83m	21.94l	21.83m	21.83m	21.15k
TGx_24_9NG-0025	33.66hi	33.77gh	33.66hi	33.66hi	49.93c
TGx_24_13NG-0031	37.31g	37.51f	37.31g	37.31g	42.84de
TGx_24_15NG-0034	50.27c	50.18c	50.27c	50.27c	49.94c
TGx_24_17NG-0039	32.46ij	32.62hi	32.46ij	32.46ij	37.21f
TGx_24_27NG-0057	42.73ef	42.84de	42.73ef	42.73ef	33.82g
TGx_24_29NG-0061	50.07cd	50.00c	50.07cd	50.07cd	21.68k
TGx_24_40NG-0088	31.93j	30.00i	31.93j	31.93j	31.93h
TGx_24_40NG-0091	21.04m	21.09l	21.04m	21.04m	65.81a
TGx_24_42NG-0100	37.40g	37.62f	37.40g	37.40g	37.24f
TGx_24_43NG-0108	29.93k	30.27j	29.93k	29.93k	23.81j
TGx_24_43NG-0126	65.67a	65.79a	65.67a	65.67a	52.23b
TGx_24_11NG-0028	34.41h	34.58g	34.41h	34.41h	42.03e
TGx 1904-6F	43.83e	43.96d	43.83e	43.83e	44.08d
TGx 2024-7E	44.08e	44.09d	44.08e	44.08e	34.89g
TGx 1835-10E	48.58d	48.74c	48.58d	48.58d	48.58c
SE±	0.11	0.23	0.11	0.11	0.23

Means followed by the same within the column are not significantly different at $p \leq 0.05$ from each other by Duncan Multiple Range Test, SE- Standard Error, JSTU- Joseph Sarwuan Tarka University, Markudi

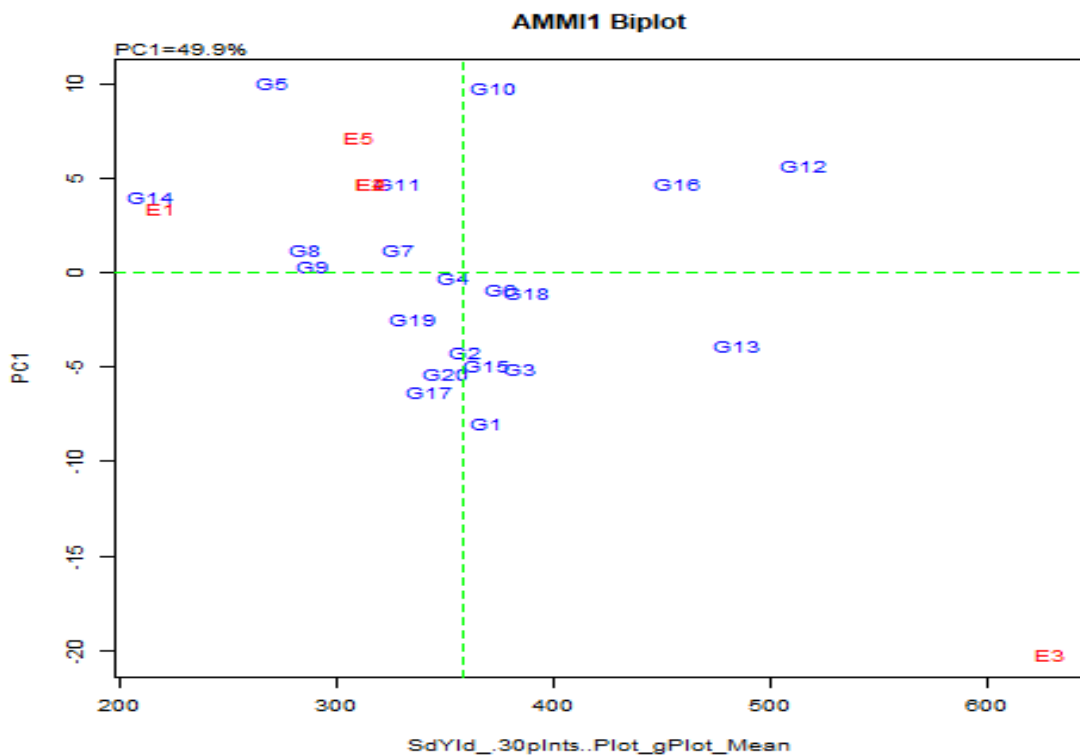


Figure 1: AMMI biplot for seed yield (g) of Twenty Soybean genotypes (G) and five environments (E) using genotypic and environmental scores.

Genotypes: G1 (TGx_24_2NG-0003), G2 (TGx_24_2NG-0005), G3 (TGx_24_9NG-0023), G4 (TGx_24_9NG-0023), G5 (TGx_24_9NG-0024), G6 (TGx_24_9NG-0025), G7 (TGx_24_13NG-0031), G8 (TGx_24_15NG-0034), G9 (TGx_24_17NG-0039), G10 (TGx_24_27NG-0057), G11 (TGx_24_29NG-0061), G12 (TGx_24_40NG-0088), G13 (TGx_24_40NG-0091), G14 (TGx_24_42NG-0100), G15 (TGx_24_43NG-0108), G16 (TGx_24_43NG-0126), G17 (TGx_24_11NG-0028), G18 (TGx 1904-6F-Check), G19 (TGx 2024-7E-Check) and G20 (TGx 1835-10E-Check)

Environments: E1 (Badeggi), E2 (Amakama), E3 (Numan), E4 (Yandev) and E5 (Joseph Sarwuan Tarka University, Markudi)

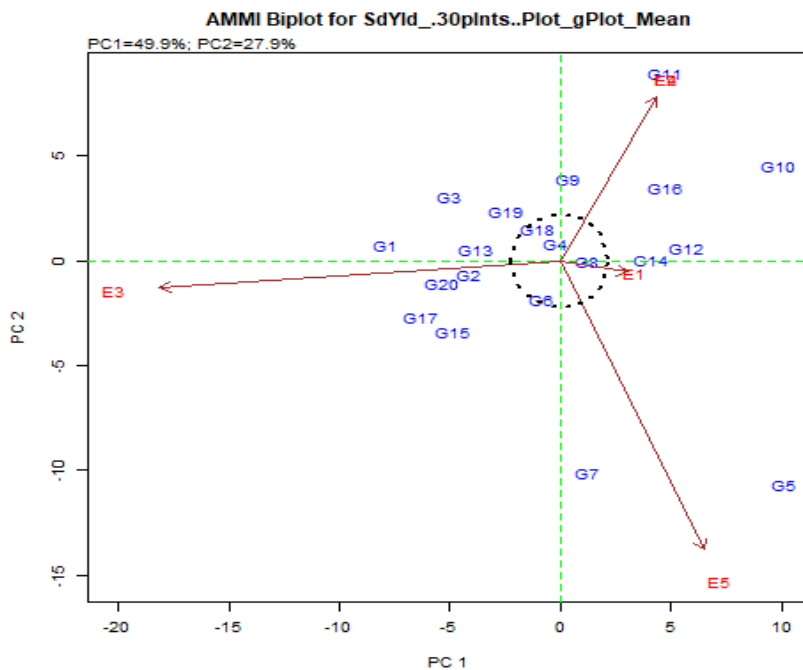


Figure 2: AMMI 2 biplot for seed yield/plot (g) showing the interaction of IPCA2 against IPCA1 scores of 20 soybean genotypes (G) in five environments (E).

Genotypes: G1 (TGx_24_2NG-0003), G2 (TGx_24_2NG-0005), G3 (TGx_24_9NG-0023), G4 (TGx_24_9NG-0023), G5 (TGx_24_9NG-0024), G6 (TGx_24_9NG-0025), G7 (TGx_24_13NG-0031), G8 (TGx_24_15NG-0034), G9 (TGx_24_17NG-0039), G10 (TGx_24_27NG-0057), G11 (TGx_24_29NG-0061), G12 (TGx_24_40NG-0088), G13 (TGx_24_40NG-0091), G14 (TGx_24_42NG-0100), G15 (TGx_24_43NG-0108), G16 (TGx_24_43NG-0126), G17 (TGx_24_11NG-0028), G18 (TGx 1904-6F-Check), G19 (TGx 2024-7E-Check) and G20 (TGx 1835-10E-Check)

Environments: E1 (Badeggi), E2 (Amakama), E3 (Numan), E4 (Yandev) and E5 (Joseph Sarwuan Tarka University, Markudi)

Figure 3 shows GGE biplot genotype view. It revealed that the bold line with double arrow head measured the degree of stability while the dotted blue line measured average yield. The genotype at the centre of the concentric circle is the ideal genotype which is also the most responsive genotype to a better environment. An ideal genotype is that genotype that is high yielding across all test environments and it is absolutely stable, TGx_24_40NG-0088 was identified as the ideal genotype although, other TGx_24_40NG-0091 and TGx_24_43NG-0126 were also in the concentric circle. Genotypes carrying longer vectors are unstable while genotypes with short vectors are stable genotypes.

Genotype TGx_24_9NG-0025, TGx_24_13NG-0031, TGx_24_15NG-0034, TGx_24_17NG-0039 and TGx 1904-6F (check) are the stable genotypes while other genotypes are unstable.

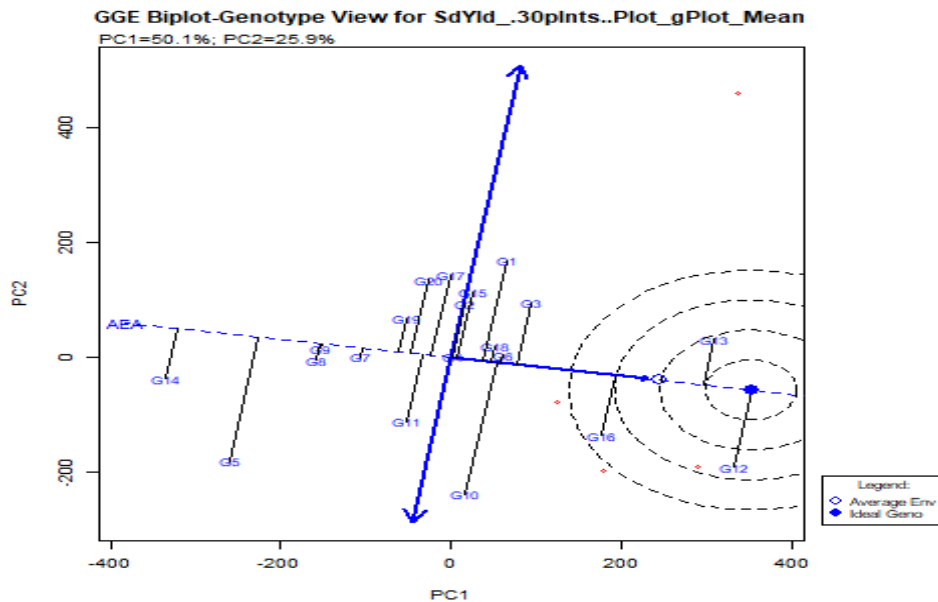


Figure 3: GGE biplot Ranking genotypes based on mean grain yield and stability across environments

Genotypes: G1 (TGx_24_2NG-0003), G2 (TGx_24_2NG-0005), G3 (TGx_24_9NG-0023), G4 (TGx_24_9NG-0023), G5 (TGx_24_9NG-0024), G6 (TGx_24_9NG-0025), G7 (TGx_24_13NG-0031), G8 (TGx_24_15NG-0034), G9 (TGx_24_17NG-0039), G10 (TGx_24_27NG-0057), G11 (TGx_24_29NG-0061), G12 (TGx_24_40NG-0088), G13 (TGx_24_40NG-0091), G14 (TGx_24_42NG-0100), G15 (TGx_24_43NG-0108), G16 (TGx_24_43NG-0126), G17 (TGx_24_11NG-0028), G18 (TGx 1904-6F-Check), G19 (TGx 2024-7E-Check) and G20 (TGx 1835-10E-Check)

Environments: E1 (Badeggi), E2 (Amakama), E3 (Numan), E4 (Yandev) and E5 (Joseph Sarwuan Tarka University, Markudi)

DISCUSSION

The evaluation of twenty soybean genotypes across five contrasting environments in Nigeria provided a critical insight into the magnitude and nature of genotype by environment interaction (GEI), as well as the adaptability and stability of climate-smart soybean varieties. The findings from mean results and the GEI pattern derived from AMMI and GGE techniques collectively demonstrate that environmental variability plays a major role in shaping soybean yield potential and stability. This agrees with earlier studies emphasizing that soybean performance is jointly governed by genetic factors and environmental influences (Ngwu *et al.*, 2023).

Several genotypes demonstrated consistently strong performance across multiple traits. For example, G12 (TGx_24_40NG-0088) and G16 (TGx_24_43NG-0126) recorded high average seed yield and strong main (additive) effects across environments. Although they were not specifically adapted to individual environments (due to their higher IPCA scores), their overall performance indicates strong genetic potential for high yield.

The AMMI analysis revealed substantial GEI effects, confirming earlier studies that soybean grain yield is one of the most GEI-sensitive traits (Kumawat *et al.*, 2020; Ngwu *et al.*, 2023). The environments E1 (Badeggi), E2 (Amakama), E4 (Yandev), and E5 (Joseph Sarwuan Tarka University, Makurdi) grouped closely together implying that these four locations exerted similar environmental pressure on genotypic performance in terms of yield response. Numan (E3) stood out as a distinct



environment, likely due to its higher temperatures and lower humidity, making it a stress-prone site. Such environments help identify stress-tolerant genotypes, for instance G6 (TGx_24_9NG-0025) and G18 (TGx 1904-6F), which showed near-zero IPCA1 scores and therefore high stability across environments. This aligns with Kurasiak-Popowska *et al.* (2024), who noted that genotypes with IPCA scores approaching zero exhibit wide stability and are suited for mega-environment targeting.

The AMMI 1 biplot showed that G2 and G16 had the **highest positive additive (main) effects** for yield, meaning they were inherently high-yielding genotypes across environments. However, both had **higher IPCA1 scores**, indicating low stability and specific adaptation rather than broad adaptation. These genotypes may therefore perform exceptionally well **only in favourable environments**, particularly the wetter sites like Amakama and Yandev. Genotypes closest to zero on the IPCA1 axis were the most stable. These included **G8, G9, G7, G6 and G18**. These genotypes showed minimal interaction with environments and thus consistent performance across sites. GGE theory confirms that such genotypes are suitable for broad adoption across large production zones (Nataraj *et al.*, 2021).

The GGE biplot is used to determine mega-environments and the highest yielding genotype in each sector (Yan *et al.*, 2021; Mehmet *et al.*, 2019). The Mega environment was Numan with Genotype G16 and G12. This aligns with earlier studies (Wenbo *et al.*, 2024), which suggest that stable genotypes tend to dominate in marginal conditions, whereas high-yielding but unstable lines dominate in favorable zones. The study aligns with Nigeria's rising vulnerability to climate variability (Yanagi, 2024; Butu *et al.*, 2022). Identifying genotypes that tolerate environmental stress while maintaining yield stability is pivotal for climate-smart agriculture. **G6, G7, G8, G9 and G18 adapted to wide environment. Although, G12 and G16** are ideal for environments with high rainfall and temperature variability, especially humid zones like Amakama.

CONCLUSION AND RECOMMENDATION

This multi-environment evaluation of climate-smart soybean genotypes revealed a substantial genetic variability, strong environmental influence across the five test sites. Genotypes exhibited different performance patterns across locations, confirming the need for multi-location testing in soybean improvement. Based on the findings from the multi-environment trials, the following recommendations are made: The genotypes **TGx_24_9NG-0025, TGx_24_13NG-0031, TGx_24_15NG-0034, TGx_24_15NG-0034, TGx_24_17NG-0039 and TGx 1904-6F** should be considered for release as widely adapted climate-smart soybean varieties in Nigeria. These genotypes consistently performed well across all environments and showed high stability in AMMI and GGE analyses.

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