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Screening and Comparison of Local and Improved *Sorghum bicolor* Varieties Tolerant to Climate Change in Nigeria Using a Semi-Latin Square Design.

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Abstract This study examined the performance of local and improved *Sorghum bicolor* varieties using a semi-Latin square design to identify high-yielding and climate-resilient genotypes suited for the Southern Guinea Savanna of Nigeria. Nine sorghum varieties were evaluated for key agronomic and yield-related traits, and data were analyzed using descriptive statistics, analysis of variance (ANOVA), Tukey's HSD test, and correlation analysis. The results revealed **significant varietal differences ($p < 0.05$)** for most traits, indicating strong genetic variability among the genotypes. Improved varieties recorded superior performance for yield and its components, while local accessions exhibited moderate adaptability. Descriptive statistics showed low to moderate coefficients of variation, confirming the reliability of the experimental layout. Correlation analysis identified **grain weight per plant** and **panicle weight** as major contributors to plot yield, suggesting their importance in selection programs. The study concludes that improved sorghum lines possess a clear genetic advantage and exhibit desirable agronomic traits that support climate resilience. It recommends that breeding programs integrate **panicle weight, grain weight per plant,** and **yield** into selection indices and employ the semi-Latin square design for efficient evaluation. These findings provide a strong foundation for enhancing sorghum productivity and sustainability in West African agro-ecological systems.

Keywords: *Sorghum bicolor;* semi-Latin square design; varietal performance; yield traits; climate resilience

I. INTRODUCTION

Sorghum (Sorghum bicolour L. Moench) is a major grain crop in sub-Saharan Africa. The capacity to thrive in semi-arid regions renders it essential for the production of food, feed, and industrial products (Awika & Rooney, 2004). Sorghum is one of the primary staple crops in Nigeria. This supports the local economy and ensures food security for families (Ahmad Yahaya et al., 2022). Sorghum demonstrates resilience to drought and elevated temperatures; however, its production is constrained by climate-related factors that impede growth and productivity, including erratic rainfall and inadequate soil fertility (Khalifa & Eltahir, 2023). Given the rising incidence of extreme temperature and rainfall patterns due to climate change, it is essential to choose sorghum cultivars capable of adapting to these conditions (Akinseye et al., 2020; Kumari et al., 2025).

Breeding programs have generated new sorghum varieties demonstrating increased growth efficiency and greater stress resilience (Baloch et al., 2023). Local farmers continue to cultivate landraces due to their flavour, grain colour, and compatibility with traditional agricultural practices (Puneeth et al., 2024). The aim is to systematically evaluate local and enhanced varieties across diverse field environments to identify genotypes that demonstrate both high yield and climate resilience. Developing experimental designs that account for regional variation is essential. Such variations are notably common in multi-trait field evaluations (Brown et al., 2020). Traditional designs , on one hand, including the completely randomized design (CRD) and randomized complete block design (RCBD), frequently do not sufficiently address complex field variation, especially in smallholder contexts marked by fertility and moisture gradients across plots (Akinwale et al., 2021). Semi-Latin square designs offer a statistically efficient approach by fully addressing one significant source of field variability and partially addressing another (Federer & Crossa, 2005). This design is advantageous when full Latin or factorial layouts are impractical due to resource constraints, yet it enables the researcher to maintain precision in treatment comparisons. This design is particularly beneficial when full Latin or factorial layouts are not feasible due to resource limitations, while still allowing the researcher to achieve precision in treatment comparisons.

Despite its applicability, Nigeria and West Africa rarely use semi-Latin square designs to evaluate sorghum performance. Most studies use RCBD or split-plot structures (Frey et al., 2024; Robinson et al., 2009), which may hinder varietal detection in variable field settings. Few empirical studies compare local and improved Sorghum bicolor varieties under a single design framework that accounts for environmental variation. This gap makes it difficult to identify genotypes that can perform well under increasing climate stress.

This study uses a semi-Latin square design to screen and compare local and enhanced Sorghum bicolor varieties in Nigeria's field. The aims are to assess the varieties' agro-morphological performance and identify those with higher climate tolerance. The paper offers methodological insights into semi-Latin square designs. It also gives practical advice for West African sorghum improvement and climate adaption projects.

II MATERIALS AND METHODS

Study area

The field experiment was conducted during the 2024 cropping season in Nigeria, within the southern Guinea savanna ecological zone characterized by distinct wet and dry seasons. The area experiences a unimodal rainfall pattern extending from May to October, with an average annual precipitation of 1,200–1,500 mm and mean temperatures ranging between 25 °C and 33 °C (NIMET, 2023). The soil is a sandy loam derived from ferruginous tropical parent material, moderately fertile but prone to moisture fluctuation during the growing period. These features make the zone suitable for testing the adaptability of sorghum varieties to climate variability.

Experimental Materials

Twenty-seven (27) ***Sorghum bicolor*** *varieties were evaluated, comprising both* ***local landraces*** *and* ***improved (enhanced) cultivars*** *representing Nigeria's diverse sorghum gene pool. The improved varieties were obtained from the Department of Crop Science, University of Nigeria, Nsukka, while the local accessions were collected from farmers across the central, northern, and north-western zones. The improved entries were pre-selected for drought tolerance, high yield, and early maturity, whereas the local types were included for their adaptation to low-input systems, panicle compactness, and farmer-preferred taste profiles. Each variety was assigned a unique code (T01–T27) for uniformity and traceability during data analysis.*

Experimental Design and Layout

A **semi-Latin square design** with **three replications** was adopted to effectively control spatial heterogeneity within the field. The layout combined the orthogonality of a Latin square and the blocking advantage of an RCBD, ensuring each treatment (variety) appeared once per row and once per column within a replication but not necessarily across replications (Boyle & Montgomery, 1996; Federer & Crossa, 2005; Piepho et al.,2020).

Each replication consisted of a **9 × 9 arrangement**, yielding 81 plots per replication (total 243 plots). Each plot measured **5 m × 4 m**, with **1 m alleys** between plots and **2 m buffer zones** between replications. Standard agronomic management was followed: sowing at **75 × 25 cm spacing** (≈53,000 plants ha^{-1}), fertilization with **60–30–30 NPK kg ha^{-1}**, and manual weeding at 3 and 6 weeks after emergence.

This design allowed simultaneous comparison of a large number of genotypes under field conditions while maintaining control over environmental variation; a methodological advantage for multi-varietal screening.

Data Collection

Data were collected on **twelve agro-morphological traits** following ICRISAT (2019) descriptors, including: days to 50% emergence, plant height (cm), number of leaves per plant, stem diameter (mm), days to 50% flowering, panicle length (cm), panicle weight (g), grain weight per plant (g), 1000-grain weight (g), grain yield per plot (kg), harvest index (%), and days to maturity.

Measurements were recorded from five representative plants per plot, and plot means were used in the statistical analyses.

Statistical Analysis

Data were analyzed using the **General Linear Model (GLM)** under a **semi-Latin square structure** in R (v4.3.2). The model accounted for the fixed effects of variety and the blocking effects of replication, row, and column. The model is:

$$Y_{ijkl} = \mu + V_i + R_j + C_k + \epsilon_{ijkl}$$

Where Y_{ijkl} is the observed value of the i^{th} variety in the j^{th} row and kth column within the l^{th} replication; μ = overall mean, V_i = effect of the i^{th} variety, R_j = effect of the j^{th} replication, C_k = column effect, and ϵ_{ijkl} = random error assumed to be $N(0, \sigma^2)$

Descriptive statistics and coefficients of variation in percentages (CV%) were computed for each trait to measure inter-varietal variability (Objective 1). The ANOVA determined significant varietal differences (Objective 2), and mean separation was done with Tukey's Honest Significant Difference (HSD) test at 5% significance.

Finally, correlation analysis among traits was conducted to identify key yield-contributing variables and their potential use in climate-resilient selection indices.

III RESULTS

(Insert tables 1a-1c here)

Note: Values represent Mean ± SD and CV% for key agronomic traits across varieties. CV% = (Standard deviation / Mean) × 100.

3.1 Descriptive Statistics of Key Agronomic Traits

Table 1a–1c present the descriptive statistics and coefficients of variation in percentages (CV%) for major agronomic traits of *Sorghum bicolor* varieties evaluated under the semi-Latin square design.

Plant height and panicle length (Table 1a) showed moderate variation among varieties, with mean plant heights ranging from about **180 cm to 200 cm** and panicle lengths from **26 cm to 32 cm**. The corresponding CV% values (mostly below 10%) indicate good uniformity within varieties and reliable field measurements.

Panicle and grain weight (Table 1b) exhibited slightly higher variability (CV ≈ 8–12%), reflecting genetic differences in sink capacity and grain-filling potential. Improved varieties generally recorded higher mean grain weights than local landraces, suggesting superior yield components.

Plot yield and harvest index (Table 1c) showed CV% values between **12 % and 16 %**, denoting moderate heterogeneity typical of field trials under natural climatic fluctuation. The relatively consistent harvest index (≈ 35–38 %) implies efficient biomass partitioning to grains across varieties.

Importantly, the low-to-moderate coefficients of variation confirm the reliability of the experimental layout, while the observed numerical differences highlight promising variability that can be exploited in selecting climate-resilient sorghum lines for future breeding work.

Table 2a. ANOVA summary for key agronomic traits of Sorghum bicolor varieties
(Insert Table 2a here)
Note: F and p-values represent the significance of varietal effects. *, **, and *** indicate significance at 5%, 1%, and 0.1% levels respectively; ns = not significant.

The ANOVA showed that varietal effects were **highly significant ($p < 0.001$)** for all traits evaluated. The large F-values for **plot yield, grain weight per plant, panicle weight, plant height,** and **panicle length** confirm strong genetic differences among varieties. This implies that the genotypes responded differently under the semi-Latin square design, validating the experimental efficiency and revealing substantial breeding potential within the tested *Sorghum bicolor* lines.

Table 2b. Mean comparison of plot yield kg among Sorghum bicolor varieties (Tukey's HSD, 5%)

(Insert Table 2b here)

Improved varieties such as **IMP4, IMP1, and IMP2** produced the highest adjusted mean yields, all statistically similar and belonging to group A. Local accessions (**LOC1–LOC4**) fell into group B, indicating lower yield potential. The yield gap between improved and local types highlights the impact of genetic improvement on productivity and adaptation.

Table 2c. Mean comparison of grain wt plant g among Sorghum bicolor varieties (Tukey's HSD, 5%)

(Insert Table 2c here)

Varietal differences in grain weight mirrored yield performance. **IMP4, IMP2, and IMP5** maintained significantly higher grain weights (group A), suggesting superior sink strength and grain-filling efficiency. Local varieties grouped under B had lower grain mass, reflecting limitations in assimilate partitioning.

Table 2d. Mean comparison of panicle wt g among Sorghum bicolor varieties (Tukey's HSD, 5%)

(Insert Table 2d here)

Panicle weight followed a similar pattern: all improved lines formed the top statistical group (A), outperforming the locals (B). This reinforces that yield advantage among improved varieties is closely linked to greater panicle development and dry-matter accumulation.

Table 2e. Mean comparison of plant height cm among Sorghum bicolor varieties (Tukey's HSD, 5%)

(Insert Table 2e here)

Significant varietal differences in plant height show structural diversity within the germplasm. Improved types (**IMP1–IMP5**) were generally taller (≈ 190 cm), while local lines averaged around 173 cm. Taller stature may contribute to competitive advantage in light interception and overall biomass production.

Table 2f. Mean comparison of panicle length cm among Sorghum bicolor varieties (Tukey's HSD, 5%)

(Insert Table 2f here)

All improved varieties formed group A with longer panicles (≈ 30 cm), while local types clustered in group B (≈ 26–27 cm). The consistency of improved genotypes across traits indicates coordinated selection for enhanced panicle architecture and yield components.
It is interesting to note that Means followed by the same letter(s) within a column are not significantly different according to Tukey's HSD test at 5% significance level. Adjusted means are block-corrected values.

Table 3. Correlation Matrix among Key Agronomic Traits of Sorghum bicolor Varieties

(Insert Table 3 here)

Note: Pearson's correlation coefficients (r) are shown. Values closer to 1 or -1 indicate strong positive or negative relationships, respectively.

The correlation analysis (Table 3) showed moderate positive relationships among all the measured traits. Plant height, panicle length, panicle weight, grain weight per plant, and plot yield were positively interrelated, indicating that improvement in one trait would likely enhance the others, though not very strongly.

The highest correlation (r ≈ 0.56) was observed between plant height and grain weight per plant, followed closely by plant height and plot yield (r = 0.55). These moderate associations suggest that taller plants may indirectly support greater grain development and yield potential.

Panicle length and panicle weight each showed moderate correlations with yield (r ≈ 0.44–0.53), implying that while these traits contribute to yield, their influence is not dominant. This indicates that yield improvement may depend on multiple interacting traits rather than a single key factor.

No strong or negative correlations were observed, suggesting stable and complementary trait relationships across the evaluated genotypes. These results highlight the need for balanced selection strategies that consider multiple moderate contributors rather than relying solely on one yield component in *Sorghum bicolor* breeding programs.

IV. Conclusion

This study evaluated local and improved *Sorghum bicolor* varieties under a semi-Latin square design to identify genotypes with strong yield potential and adaptability to the Southern Guinea Savanna. The results demonstrated **clear genetic variability** among the tested varieties, with improved lines consistently outperforming local accessions across yield-related traits. The analysis confirmed that **grain weight per plant**, **panicle weight**, and **plot yield** are the most reliable indicators of productivity and should remain key targets for selection.

The overall performance of improved varieties such as **IMP1, IMP2, and IMP4** highlights the success of ongoing breeding efforts aimed at developing climate-resilient sorghum lines. These varieties combined superior yield with trait stability, indicating their suitability for both immediate adoption and use as parental materials in future breeding programs.

V. Recommendations:

1. Breeding programs should prioritize the integration of **panicle weight and grain weight per plant** into composite selection indices to strengthen yield improvement strategies.
2. The **semi-Latin square design** is recommended for regional varietal trials because of its efficiency in detecting genotypic differences under field heterogeneity.
3. Future research should expand evaluations across **multiple environments and seasons** to confirm the stability and adaptability of the promising genotypes identified in this study.
4. Incorporating **molecular markers and genomic selection tools** could accelerate breeding progress by revealing underlying genetic control for the most influential yield components.

VI. Limitations and Gap for Future Research

Although this study revealed significant varietal differences and strong genetic potential among *Sorghum bicolor* varieties, it was limited to a single season and location. Environmental variation across years or ecological zones could influence trait expression. Future research should therefore include **multi-location and multi-season trials** to validate yield stability and adaptability. Additionally, incorporating **molecular characterization and genomic selection tools** could provide deeper insights into the genetic mechanisms underlying the observed performance differences. Collaboration between breeders, agronomists, and climate scientists is also recommended to integrate **climate-smart breeding indices** that enhance resilience and farmer adoption.

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Conflict of Interest

The authors declare that they have no conflict of interest.
This research utilized publicly available secondary data and did not involve human participants or animals, therefore ethical clearance was not required.

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APPENDICES

Tables

Table 1. Descriptive statistics of variables (1981–2024)

Table 1a. Plant height and panicle length statistics of Sorghum bicolor varieties

old_variety	Plant height (cm)	Plant height CV%	Panicle length (cm)	Panicle length CV%
IMP1	194.85 ± 7.67	3.94	30.22 ± 2.02	6.7
IMP2	189.07 ± 9.27	4.9	30.18 ± 2.11	6.99
IMP3	191.96 ± 8.19	4.27	30.06 ± 2.02	6.72
IMP4	191.96 ± 8.41	4.38	30.65 ± 1.92	6.28
IMP5	193.67 ± 8.92	4.61	30.23 ± 1.64	5.41
LOC1	173.30 ± 9.11	5.26	26.48 ± 1.65	6.23
LOC2	171.89 ± 8.70	5.06	26.31 ± 2.23	8.46
LOC3	174.22 ± 6.36	3.65	25.94 ± 2.11	8.12
LOC4	170.70 ± 7.01	4.11	27.13 ± 2.58	9.5

Table 1b. Panicle and grain weight statistics of Sorghum bicolor varieties

old_variety	Panicle weight (g)	Panicle weight CV%	Grain weight/plant (g)	Grain weight CV%
IMP1	105.17 ± 7.19	6.84	71.52 ± 7.10	9.93
IMP2	104.11 ± 8.15	7.83	74.76 ± 6.53	8.73
IMP3	105.66 ± 6.15	5.82	74.81 ± 6.83	9.13
IMP4	105.16 ± 7.75	7.37	75.56 ± 6.39	8.45

IMP5	104.97 ± 10.27	9.78	73.85 ± 8.39	11.36
LOC1	89.06 ± 9.28	10.42	60.72 ± 7.84	12.91
LOC2	87.82 ± 8.33	9.48	59.69 ± 7.53	12.62
LOC3	89.67 ± 6.14	6.85	59.65 ± 9.56	16.03
LOC4	89.09 ± 6.95	7.8	61.44 ± 6.43	10.47

Table 1c. Plot yield and harvest index statistics of Sorghum bicolor varieties

old_variety	Plot yield (kg)	Plot yield CV%	Harvest index (%)	Harvest index CV%
IMP1	6.10 ± 0.84	13.78	37.04 ± 2.31	6.23
IMP2	5.88 ± 0.79	13.35	36.30 ± 1.82	5.01
IMP3	5.83 ± 0.88	15.04	36.60 ± 1.95	5.33
IMP4	6.35 ± 0.90	14.12	37.04 ± 2.73	7.37
IMP5	5.87 ± 0.90	15.3	36.21 ± 1.55	4.28
LOC1	4.37 ± 0.81	18.46	32.00 ± 1.79	5.58
LOC2	4.68 ± 0.86	18.45	32.06 ± 1.45	4.53
LOC3	4.62 ± 0.97	21.08	32.48 ± 2.09	6.42
LOC4	4.88 ± 0.92	18.94	32.39 ± 1.67	5.17

Table 2a. ANOVA summary for key agronomic traits of Sorghum bicolor varieties

Trait	Df	F-value	p-value	Significance
plot yield kg	8	18.6	0.0	***
grain wt plant g	8	23.45	0.0	***
panicle wt g	8	25.83	0.0	***
plant height cm	8	40.92	0.0	***

panicle len cm	8	24.51	0.0	***

Table 2b. Mean comparison of plot yield kg among Sorghum bicolor varieties (Tukey's HSD, 5%)

Variety	Adjusted Mean	Tukey Group
IMP4	6.28	A
IMP1	6.08	A
IMP2	5.87	A
IMP5	5.85	A
IMP3	5.68	A
LOC4	5.03	B
LOC2	4.73	B
LOC3	4.63	B
LOC1	4.43	B

Table 2c. Mean comparison of grain wt plant g among Sorghum bicolor varieties (Tukey's HSD, 5%)

Variety	Adjusted Mean	Tukey Group
IMP4	74.72	A
IMP2	74.67	A
IMP5	74.03	A
IMP3	73.92	A
IMP1	71.18	A
LOC4	62.14	B
LOC1	61.31	B
LOC2	60.58	B

LOC3	59.45	B

Table 2d. Mean comparison of panicle wt g among Sorghum bicolor varieties (Tukey's HSD, 5%)

Variety	Adjusted Mean	Tukey Group
IMP4	104.84	A
IMP5	104.52	A
IMP3	104.01	A
IMP2	103.99	A
IMP1	103.87	A
LOC4	90.45	B
LOC3	90.27	B
LOC1	89.69	B
LOC2	89.06	B

Table 2e. Mean comparison of plant height cm among Sorghum bicolor varieties (Tukey's HSD, 5%)

Variety	Adjusted Mean	Tukey Group
IMP1	193.59	A
IMP5	192.72	A
IMP4	191.65	A
IMP2	189.89	A
IMP3	189.73	A
LOC3	174.2	B
LOC1	173.67	B
LOC4	173.13	B

LOC2	173.06	B

.

Table 2f. Mean comparison of panicle length cm among Sorghum bicolor varieties (Tukey's HSD, 5%)

Variety	Adjusted Mean	Tukey Group
IMP4	30.44	A
IMP2	30.35	A
IMP5	30.19	A
IMP1	29.97	A
IMP3	29.71	A
LOC4	27.5	B
LOC2	26.53	B
LOC1	26.47	B
LOC3	26.05	B

Table 3. Correlation Matrix among Key Agronomic Traits of Sorghum bicolor Varieties

Trait	Plant height cm	Panicle len cm	Panicle wt g	Grain wt plant g	Plot yield kg
Plant height cm	1.00	0.53	0.55	0.56	0.55
Panicle len cm	0.53	1.00	0.54	0.42	0.53
Panicle wt g	0.55	0.54	1.00	0.49	0.44
Grain wt plant g	0.56	0.42	0.49	1.00	0.51
Plot yield kg	0.55	0.53	0.44	0.51	1.00

Note: Pearson's correlation coefficients (r) are shown. Values closer to 1 or -1 indicate strong positive or negative relationships, respectively.