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Research article

Genetic Analysis and Hybrid Performance of Drought- and Low-Nitrogen-Tolerant Maize (*Zea mays* L.) Inbred Lines Under Drought and Rainfed Conditions

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ABSTRACT

Climate change projections indicate an increasing frequency and severity of drought events in the coming years, posing a serious threat to maize production. The Institute for Agricultural Research (IAR), Zaria, Nigeria, has therefore prioritized the development of drought-tolerant maize varieties. Fifty-five maize hybrids, derived through diallel crosses involving 11 drought- and low-nitrogen-tolerant inbred lines, were evaluated under drought-stressed and rainfed conditions at two locations in the Guinea and Derived Savanna zones of Nigeria (2021–2023). The objectives were to assess the general (GCA) and specific (SCA) combining abilities of the lines and to identify high-yielding, drought-tolerant, and stable hybrids. Significant GCA and SCA effects ($p < 0.01$) were observed for most traits under both conditions, indicating that both additive and non-additive gene effects contribute to trait inheritance, with additive effects predominating. High predictive ratios (>0.8) for most traits indicated that GCA was a reliable predictor of hybrid performance. Inbreds SMLW-156 and SMLW-163 were identified as outstanding general combiners for grain yield and key adaptive traits, making them valuable for hybrid development and for introgressing favorable alleles into breeding populations. Drought tolerance was assessed using three multi-trait selection indices (Base Index, Drought Selection Index and Selection Index based on Trait Points), which consistently identified 14 drought-tolerant hybrids. Among these, SMLW-99 × SMLW-156, the top-performing hybrid in the study, is recommended for cultivation in drought-prone areas due to its high yields under both drought-stressed (3,937 kg/ha) and rainfed (8,642 kg/ha) conditions, high drought-tolerance scores, and moderate yield stability. SMLW-163 × SMLW-156, which recorded the highest yield under rainfed conditions (8,733 kg/ha), is best suited for regions with reliable rainfall.

Key words:
general combining ability; specific combining ability, grain yield, stability analysis, selection indices, GGE biplot analysis

Abbreviations:
ANOVA – Analysis of Variance; ASI – anthesis-silking interval; BI – Base Index; DAT – days to anthesis; DSK – days to silking; EAS – ear aspect; EHT – ear height; EPP – ears per plant; GCA – general combining ability; GY – grain yield; HC – husk cover; IAR – Institute for Agricultural Research; IN – Drought Selection Index; LDS – leaf death score; PAS – plant aspect; PHT – plant height; SCA – specific combining ability; SIP – Selection Index Based on Trait Points; WAP – weeks after planting

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INTRODUCTION

Drought remains one of the most critical abiotic stresses limiting crop productivity worldwide, particularly in sub-Saharan Africa (Badu-Apraku et al., 2021; Bankole et al., 2017). Maize, a staple food crop widely cultivated under rainfed conditions across sub-Saharan Africa, is especially susceptible to moisture deficits. In Nigeria, the Northern, Southern, and Derived Savanna agroecological zones, which are major maize-producing areas, are especially prone to drought due to their unimodal rainfall distribution and increasing inter-annual climatic variability (Ayanlade et al., 2018; Kamara et al., 2020). This vulnerability is further exacerbated by the limited access to irrigation infrastructure, leaving most farmers heavily reliant on the timing and distribution of seasonal rainfall.

The consequences of drought stress in maize are profound, with short-term drought episodes capable of causing substantial physiological disruptions and yield losses exceeding 50%, depending on the timing and severity of the stress (Badu-Apraku et al., 2021; Menkir et al., 2024). Drought during flowering is particularly damaging, as it can prolong the anthesis-silking interval, disrupt synchrony between pollen shed and silking, and result in poor fertilization and increased kernel abortion (Badu-Apraku et al., 2021; Zia et al., 2021). Post-flowering drought is also detrimental, as it restricts carbohydrate accumulation and grain filling, ultimately reducing kernel weight and overall yield potential (Zia et al., 2021).

As part of its efforts to develop maize varieties with improved drought tolerance, the Institute for Agricultural Research (IAR), Zaria, Nigeria, has developed several inbred lines with promising levels of drought tolerance. However, although the *per se* performance of these inbreds has been determined, their combining ability under stress conditions remains largely unexplored. This knowledge gap is significant because hybrid performance depends not only on the genetic potential of individual parents but also on the interactions between them (Aboderin et al., 2024a; Ertiro et al., 2017).

Combining ability analysis based on estimates of GCA and SCA provides insights into the genetic contributions of parental lines and the gene actions controlling key traits (Aboderin et al., 2024a; Amegbor et al., 2023). GCA captures the average performance of a line across multiple hybrid combinations and reflects additive gene effects, while SCA accounts for deviations in the performance of specific crosses from what would be expected based on the GCA of the parents, primarily due to non-additive genetic effects (Aboderin et al., 2024a). Among the various mating designs used to estimate GCA and SCA effects, the diallel mating design is often preferred, especially when working with a limited number of new or uncharacterized inbred lines. Unlike Line × Tester or North Carolina designs, which assign fixed roles to parental lines, the diallel design enables a comprehensive and unbiased evaluation of each line's performance in multiple hybrid combinations (Falconer and Mackay, 1996; Muthoni and Shimelis, 2020). This approach increases the likelihood of identifying superior hybrid combinations by capturing both additive and non-additive effects (Falconer and Mackay, 1996).

Several studies have investigated the genetic control of grain yield under drought stress, reporting contrasting findings. While some have reported a predominant role of additive genetic effects, some studies have emphasized non-additive genetic effects, while others have highlighted contributions from both (Oyekunle and Badu-Apraku, 2014; Amegbor et al., 2023; Adebayo et al., 2017; Obeng-Bio et al., 2019). A consistent observation across these studies is that the nature of gene action is influenced by the genetic background of the germplasm and the intensity of the drought stress during evaluation. Consequently, understanding the mode of inheritance of grain yield and related traits in newly developed inbred lines is essential for guiding effective breeding strategies. Therefore, this study was undertaken to: i) determine the gene action governing grain yield and drought-tolerance-related traits in drought- and low-nitrogen-tolerant maize inbred lines under drought-stressed and rainfed conditions; ii) identify inbred lines with superior GCA and SCA estimates for use in future breeding programs; and iii) identify high-yielding, drought-tolerant, and stable hybrids.

MATERIAL AND METHODS

Genetic Materials

Eleven maize inbred lines selected for tolerance to both drought and low-nitrogen stress were used as the genetic materials in this study (Table 1). These lines are part of a newly developed set of inbred lines by the Institute for Agricultural Research (IAR), Zaria, Nigeria, which had earlier been evaluated for *per se* performance under both drought and low-N conditions (Aboderin et al., 2024a). The selected inbred lines were planted at the IAR research field located in Mokwa, Niger State, Nigeria in September 2021. In September 2021, the 11 inbred lines were planted at the IAR research field in Mokwa, Niger State, Nigeria, in a sequential block arrangement to facilitate controlled pollination following a half-diallel mating design (Griffing's Method II, Model I). In each block, the designated inbred line was planted in two rows, while the remaining lines required for crossing were planted in

adjacent single rows. The first block comprised Line 1 planted in two rows, followed by Lines 2–11 in single rows. The second block comprised Line 2 planted in two rows, followed by Lines 3–11 in single rows. This pattern continued sequentially until the final block, which comprised Lines 10 and 11, each planted in a single row. Controlled hand pollination was performed between designated parental lines to generate 55 unique single-cross hybrids. Each inbred line served as both a male and a female parent across the crossing program, depending on the specific cross. Reciprocal crosses were excluded, with only one cross produced for each pair of inbred lines. Hybrid seeds were harvested at physiological maturity, dried, processed, and stored under appropriate conditions before field evaluation.

Table 1. Pedigree and maturity of the 11 low-N and drought-tolerant maize inbred lines selected for diallel hybrids development

Lines	Pedigree	Maturity group	Origin
SMLW-24	SAM 26 S6-3-16-3-3-2-2-1-1-1-1-1-3	Intermediate maturing	IAR
SMLW-99	SAM 16 S6-2-6-1-2-3-3-1-2-1-1-1-1	Intermediate maturing	IAR
SMLW-145	TZE-W S5-5-13-3-3-1-2-1-3-1-2	Intermediate maturing	IAR
SMLW-156	SAM 26 S5-4-6-2-2-2-2-1-1-2-3	Intermediate maturing	IAR
SMLW-159	SAM 26 S5-1-12-2-2-2-2-1-1-1-2	Intermediate maturing	IAR
SMLW-167	SAM 27 S5-2-11-2-3-3-3-1-3-1-1	Late maturing	IAR
SMLW-169	TZE-W S5-3-8-2-3-1-2-2-2-1-1	Intermediate maturing	IAR
SMLW-100	TZEE-W S6-2-3-1-2-1-2-1-2-1-1-1-1	Late maturing	IAR
SMLW-146	TZE-W S5-3-13-2-2-1-2-2-2-1-2	Late maturing	IAR
SMLW-163	TZE-W S5-5-13-1-3-1-1-2-2-2-2	Late maturing	IAR
SMLW-165	TZE-W S5-2-13-3-3-2-2-1-1-1-1	Late maturing	IAR

Source: IAR (Institute for Agricultural Research)

Field evaluation and management

The 55 single-cross hybrids generated from the diallel crosses, along with their 11 parental inbred lines and one standard drought-tolerant check, were evaluated under drought-stressed and rainfed conditions at two locations in Nigeria: Mokwa, Niger State (Southern Guinea Savanna; latitude 9.28°N, longitude 5.05°E; mean annual rainfall: 1,200–1,300 mm), and Ilora, Oyo State (Derived Savanna; latitude 7.85°N, longitude 3.92°E; mean annual rainfall: 1,200–1,500 mm).

Rainfed trials were established at the onset of the rainy season at each location. In Ilora, planting was conducted in May in both 2022 and 2023, while in Mokwa, planting took place in July of both years. Drought-stressed trials were established during the dry seasons of 2021/2022 and 2022/2023, with planting carried out in late December at both locations. The dry-season planting allowed for the imposition of controlled terminal drought stress. At Ilora, some sporadic rainfall occurred during the first four weeks after planting; thus, no supplemental irrigation was applied during that period. In contrast, Mokwa experienced minimal rainfall, and supplemental irrigation was applied every five days using tanker-supplied water delivered through a hose. Irrigation was completely withdrawn 30 days after planting, just prior to flowering, to ensure that drought stress coincided with the critical reproductive stages when maize is most sensitive to moisture deficits (Menkir et al., 2024). Drought stress was maintained until physiological maturity to simulate terminal drought conditions. Except for differences in water management, all agronomic practices were kept consistent across drought-stressed and rainfed environments.

Hybrid trials were conducted using an 8 × 7 alpha-lattice design, comprising eight blocks with seven hybrids randomly assigned to each block. In each environment, the 11 parental inbred lines were evaluated separately in an adjacent block using a randomized complete block design. All experiments were replicated twice, with genotypes independently randomized in the second replication to ensure unbiased and uniform distribution. A 1-meter spacing was maintained between adjacent blocks to reduce inter-block interference. Two border rows were planted on each side of the trial area to minimize edge-row effects and promote uniform growing conditions for the central plots. Within each plot, plants were spaced 0.75 m apart between rows and 0.40 m apart within rows, targeting a plant population density of approximately 66,667 plants ha^{-1}. Fertilizer application varied based on the growing condition. Under drought-stressed conditions, a compound fertilizer (NPK 15:15:15) was applied at planting at a rate of 60 kg ha^{-1} each of nitrogen (N), phosphorus (P), and potassium (K). This was followed by a top-dressing of 60 kg N/ha as urea at three weeks after planting (WAP). Under rainfed conditions, the total recommended N rate of 90 kg N/ha was applied, consisting of 60 kg N/ha from NPK 15:15:15 applied at 2 WAP, supplemented with 30 kg N/ha as urea at 5 WAP. Weed management was tailored to each location, based on the dominant weed species present. Appropriate

pre- and post-emergence herbicides were applied, supplemented with hand weeding as necessary to ensure effective weed suppression and minimize competition between weeds and maize plants.

Data Collection

Trait measurements were conducted following standard guidelines by IAR (Aboderin et al., 2024a). Data were collected at three key stages of maize development: flowering, post-flowering, and harvest. At the flowering stage, phenological traits such as days to anthesis (DAT), days to silking (DSK), and the anthesis-silking interval (ASI) were recorded to assess developmental timing and reproductive synchrony. During the post-flowering stage, traits related to vegetative vigor and stress response were assessed. These included plant height (PHT), ear height (EHT), leaf death score (LDS), and plant aspect (PAS). LDS was evaluated only under drought-stress conditions, as it serves as a key indicator of drought tolerance. It was visually rated on a scale of 1 to 9, where 1 indicated minimal or no leaf death (i.e., green and healthy foliage), and 9 indicated complete or near-complete leaf senescence and drying. The score thus reflects the degree of leaf senescence due to drought stress, with lower scores suggesting higher drought tolerance. At the harvest stage, yield-related parameters were recorded. These included ears per plant (EPP), calculated as the total number of harvested ears divided by the total number of plants harvested per plot; ear aspect (EAS), which reflects overall ear quality and uniformity; husk cover (HC), which indicates the extent to which ears are covered by husks and thus provides an indication of grain protection; and grain yield (GY). All traits were assessed consistently across both rainfed and drought environments, with the exception of LDS and GY. GY was estimated under rainfed conditions from the weight of unshelled grain obtained from dehusked ears using an assumed shelling coefficient of 80%. In contrast, under drought-stress conditions, GY was determined from manually shelled and properly dried ears to improve accuracy, as drought stress often causes poor grain fill and irregular ear development.

Statistical Analysis

***Analysis of Variance* (ANOVA)**

A combined ANOVA was performed separately for each research condition (drought and rainfed) using the mixed model procedure (PROC MIXED) in SAS version 9.3 (SAS Institute, 2009). Each combination of location, year, and research condition was treated as a unique environment, resulting in a total of eight environments, viz: DT1 (Mokwa drought stress 2022), DT2 (Mokwa drought stress 2023), DT3 (Ilora drought stress 2022), DT4 (Ilora drought stress 2023), RF1 (Mokwa rainfed 2022), RF2 (Mokwa rainfed 2023), RF3 (Ilora rainfed 2022), RF4 (Ilora rainfed 2023). In the mixed model, environment, block, and replication effects were considered random, while genotype was treated as a fixed effect. The ANOVA model was specified as follows:

$$Y_{ijkl} = \mu + E_i + R(E)_{j(i)} + B(RxE)_{k(jl)} + G_l + (GxE)_{li} + \epsilon_{ijkl}$$

Where:
Y_{ijkl} - observed value of the trait;
μ - overall mean;
E_i - effect of the ith environment;
G_1 - genotype;
$R(E)_{j(i)}$ - effect of the jth replication within the ith environment;
$B(RxE)_{k(jl)}$ - effect of the kth block within the jth replication and ith environment;
$(GxE)_{li}$ - genotype x environment interaction,
ϵ_{ijkl} - residual error.

Combining ability analysis was performed using AGD-R software (Pacheco et al., 2016), based on Griffing's Method IV and Model I (Griffing, 1956). The relative importance of GCA and SCA effects was evaluated using the formula proposed by Baker (1978):

$$\frac{2\sigma^2{}_{GCA}}{2\sigma^2{}_{GCA} + \sigma^2{}_{SCA}}$$

Where $\sigma^2{}_{GCA}$ and $\sigma^2{}_{SCA}$ are the estimated variance components for GCA and SCA, respectively. A value close to 1 suggests that additive genetic effects (GCA) predominantly control the trait, thus making performance more predictable based on parental lines.

Selection of Drought-Tolerant Hybrids

Three multi-trait selection indices were used to identify drought-tolerant hybrids: IITA Base Index (BI), Drought Selection Index (I_N), and Selection Index Based on Trait Points (SIP). For both BI and I_N, standardized values of the component traits were used. Across all indices, hybrids with positive index values were classified as drought-tolerant, while those with negative values were considered not drought-tolerant.

$I_N = (5\ x\ YLD_{DT}) + 2EPP_{DT} - 2ASI_{DT} - 2LDS_{DT}$ (Bänziger et al., 2000)

$BI = (2\ x\ YLD_{DT}) + YLD_{RF} + EPP_{DT} - ASI_{DT} - PAS_{DT} - EAS_{DT} - LDS$ (Oyekunle and Badu-Apraku, 2014)

SIP $= nX + mY - \sum_{i=1}^{n} Drought\ trait\ values - \sum_{i=1}^{m} Rainfed\ trait\ values$ (Aboderin et al., 2024b)

Where:

YLD_{DT} - grain yield under drought;

YLD_{RF} - grain yield under rainfed;

n, *m* - number of traits measured under drought and rainfed conditions, respectively;

X, *Y* - genotypic yield scores under drought and rainfed conditions;

$\sum_{i=1}^{n}$ – trait point totals for each genotype relative to the best observed trait values across genotypes under drought-stress conditions;

$\sum_{i=1}^{m}$ – Trait point totals for each genotype relative to the best observed trait values across genotypes under rainfed conditions.

GGE Biplot Analysis

A total of 25 hybrids identified as drought-tolerant by at least two of the three selection index methods, along with one standard check, were selected for GGE biplots analysis using GEA-R software (Pacheco et al., 2016), based on their mean grain yield across the eight environments. This analysis was conducted to identify hybrids with both high mean grain yield and stable performance across drought-stressed and rainfed conditions.

RESULTS

The results of ANOVA under drought-stressed conditions revealed significant environmental (ENV) effects ($p \leq 0.05$ or $p \leq 0.01$) for all evaluated traits except EHT, PAS, and LDS (Table 2). Significant genotype (GEN) effects ($p \leq 0.05$ or $p \leq 0.01$) were observed for all traits. Genotype × environment interaction (GEI) effects were non-significant ($p > 0.05$) for all traits. Both GCA and SCA effects were significant ($p \leq 0.05$ or $p \leq 0.01$) for all traits. GCA mean squares exceeded SCA mean squares for all traits except ASI, EAS, and LDS, for which SCA mean squares were higher. GCA × ENV and SCA × ENV interaction effects were non-significant for all traits under drought-stressed conditions.

Under rainfed conditions, significant ENV effects ($p \leq 0.05$ or $p \leq 0.01$) were observed for all traits except DSK, while significant GEN effects ($p \leq 0.05$ or $p \leq 0.01$) were observed for all traits (Table 2). Significant GEI effects ($p \leq 0.05$ or $p \leq 0.01$) were detected for five traits: GY, DAT, PHT, PAS, and HC. Both GCA and SCA effects were significant ($p \leq 0.05$ or $p \leq 0.01$) for all traits except DSK and ASI, for which SCA effects were non-significant. GCA mean squares exceeded SCA mean squares for all traits. GCA × ENV and SCA × ENV interaction effects were non-significant for all traits except DSK, for which both interactions were significant ($p \leq 0.05$).

The relative importance of GCA and SCA, ranged between 0.53 (ASI) and 0.88 (PHT) under drought-stressed conditions, and varied from 0.72 (EPP) to 0.97 (PHT) under rainfed conditions. Under rainfed conditions, all measured traits, except for EPP (0.72), had high predictive ratios (> 0.90). In contrast, predictive ratios were relatively lower under drought stress. GY, PHT, EHT, and HSK had moderately high values (0.80 – 0.88), while DAS, DSK, PAS, and EPP ranged between 0.70 and 0.79. LDS showed a moderate value (0.67), while ASI (0.53) and EAS (0.56) exhibited relatively low predictive ratios (Table 2).

Combining ability effects of drought- and low-N-tolerant lines under drought-stressed and rainfed conditions

General combining ability effects

The GCA effects of the 11 low-N and drought-tolerant maize inbred lines for GY and other agronomic traits are presented in Table 3. Positive and significant GCA effects for GY under both conditions were observed for lines SMLW-156 and SMLW-163. Line SMLW-167 also showed a strong positive GCA effect under drought conditions but a significant negative effect under rainfed conditions. Conversely, SMLW-159 and SMLW-145, which were among the top general combiners for GY under rainfed conditions, showed negative but non-significant GCA effects

under drought stress. Significant negative GCA effects for GY were consistently observed for SMLW-100 and SMLW-169 under both conditions.

For the flowering traits (DAT and DSK), SMLW-100 and SMLW-145 exhibited significant negative GCA effects under drought conditions, while SMLW-169 had significant negative GCA effect under rainfed conditions. These lines also showed negative but non-significant effects in the opposite growing condition. In contrast, SMLW-159, SMLW-163, and SMLW-24 showed positive GCA effects under drought stress, while SMLW-99 and SMLW-24 had positive values under rainfed conditions. Significant negative GCA effects for ASI were observed for SMLW-165 and SMLW-169 under drought stress and for SMLW-145 under rainfed conditions.

For the growth traits (PHT and EHT), SMLW-99 showed significantly positive GCA effects under both conditions. In addition, SMLW-169 and SMLW-24 (under drought stress) and SMLW-167 (under rainfed conditions) recorded significantly positive values for both traits. Conversely, SMLW-159 had significant negative GCA effects under both conditions, with SMLW-163 (under drought stress) and SMLW-24 (under rainfed conditions) also showing negative values. Six lines showed significant negative GCA effects for PAS under drought stress, and three lines recorded significant positive GCA effects. Only SMLW-146 had a significant negative GCA effect for EAS under drought stress. Under rainfed conditions, five lines showed significant negative GCA effects for both PAS and EAS, with SMLW-156 and SMLW-99 having the most favorable values for these traits. SMLW-156 showed significant negative GCA effects for HC under both conditions. This was also observed for SMLW-167 under drought stress and for SMLW-100, SMLW-146, SMLW-163, and SMLW-99 under rainfed conditions. GCA effects for EPP were mostly non-significant or negative, except for SMLW-167 under drought stress and SMLW-146 under rainfed conditiosn, both of which had significant positive effects. For LDS, significant negative GCA effects were recorded for SMLW-156, SMLW-165, and SMLW-167, while significant positive effects were observed for SMLW-100 and SMLW-99 under drought-stressed conditions.

Specific combining ability effects

The SCA effects for GY among the lines under drought-stressed and rainfed conditions are presented in Table 4. Under drought-stressed conditions, four cross combinations viz.: SMLW-156 × SMLW-159, SMLW-146 × SMLW-163, SMLW-156 × SMLW-169, and SMLW-165 × SMLW-100 exhibited significantly positive SCA effects for GY, with SMLW-165 × SMLW-100 recording the highest value. Among these, only the SMLW-165 × SMLW-100 cross maintained a positive SCA effect under rainfed conditions, although it was not statistically significant. In contrast, the other three combinations showed negative SCA effects under rainfed conditions, with SMLW-156 × SMLW-159 being significantly negative ($p < 0.01$). Under rainfed conditions, several cross combinations showed positive SCA effects, with four crosses (SMLW-156 × SMLW-146, SMLW-167 × SMLW-163, SMLW-169 × SMLW-100, and SMLW-24 × SMLW-100) displaying statistically significant positive effects. Of these, only SMLW-169 × SMLW-100 also exhibited a positive SCA effect under drought-stressed conditions, whereas the others showed negative effects in the drought –stress environment.

Agronomic performance of the hybrids under drought-stressed and rainfed conditions

The mean GY of the hybrids was higher under rainfed conditions (5,575 kg/ha) compared to drought-stressed conditions (2,271 kg/ha), representing a 59.3% reduction in grain yield under drought stress (Table 5). Four hybrids, SMLW-167 × SMLW-163, SMLW-165 × SMLW-146, SMLW-99 × SMLW-156, and SMLW-165 × SMLW-163 recorded the highest yields under drought stress, ranging between 3,833 and 4,157 kg ha^{-1} (Table 6). These were the only hybrids that outperformed the hybrid check, with yield advantages ranging between 5.8 and 13.2%. Yield reduction under drought compared to rainfed conditions varied widely among hybrids, from as low as 8.6% in SMLW-165 × SMLW-163 to as high as 83.9 % in SMLW-159 × SMLW-100. The lowest yielding hybrids under drought were SMLW-159 × SMLW-100 and SMLW-99 × SMLW-24, with yields of 1,063 and 1,037 kg/ha, respectively. Under rainfed conditions, hybrid GY ranged between 2,466 and 8,733 kg/ha. Three hybrids (SMLW - 156 x SMLW – 100, SMLW - 24 x SMLW – 156 and SMLW - 163 x SMLW – 100) yielded between 7,000 and 8,000 kg/ha, while five hybrids (SMLW - 163 x SMLW – 156, SMLW - 99 x SMLW – 156, SMLW - 159 x SMLW – 146, SMLW - 146 x SMLW – 100, and SMLW - 163 x SMLW – 146) exceeded 8,000 kg/ha. These eight hybrids were the only ones that outyielded the hybrid check, with the highest yield advantage of 21.0% observed for SMLW-163 × SMLW-156. The lowest yielding hybrid under rainfed conditions was SMLW-167 × SMLW-169, with a yield below 3,000 kg/ha.

Table 2. Mean squares from the combined analysis of variance for grain yield and other agronomic traits of 56 maize hybrids evaluated under drought-stress and rainfed conditions at Mokwa and Ilora, Nigeria (2022-2023)

Source of variation	df	GY (kg/ha)	DAT (Days)	DSK (Days)	ASI (Days)	PHT (cm)	EHT (cm)	PAS (1 – 5)	EAS (1 – 5)	HC (1 – 5)	EPP	LDS (1-9)
Drought-stress condition												
Env	3	7587247*	54.43**	116.16**	22.22**	7187.21**	180.34	0.09	3.95*	2.66*	0.21*	4.10
Rep (Env)	4	4443819	152.63**	135.26**	0.53	1686.31**	746.27	0.11**	2.42*	0.99**	0.08	7.91**
Block (Env*Rep)	56	396883	8.48	8.01	0.76	1484.67*	1145.25**	0.83*	1.45	0.97*	0.08	4.80**
Hybrids	54	3577955*	30.72**	28.64**	2.35**	2681.66**	993.74**	5.63**	1.89*	0.98*	0.10*	333.46**
GCA	10	7036263**	35.03**	37.24**	1.42	6632.77**	76840.33**	9.26**	1.28	1.64*	0.14*	61.40*
SCA	44	2791976*	29.74**	26.69**	2.56**	1783.68**	36048.59*	4.81**	2.03*	0.83*	0.11**	272.07**
Env x Hybrids	162	2396050	9.14	8.91	1.15	983.42	70565.39	0.28	1.29	0.65	0.06	466.36
Env x GCA	30	3570700	8.19	8.81	0.76	902.30	15433.90	0.19	1.70	0.67	0.07	100.72
Env x SCA	132	2129084	9.35	8.93	1.24	1001.86	55131.48	0.30	1.20	0.65	0.07	365.65
Residual	160	1985490	9.53	9.35	0.98	911.60	73912.23	0.24	1.25	0.57	0.06	389.43
GCA:SCA Ratio		0.83	0.70	0.74	0.53	0.88	0.81	0.79	0.56	0.80	0.72	0.67
Rainfed condition												
Env	3	19402690*	4.91*	0.80	6.50*	71392.42**	14956.48**	63.79**	37.33**	16.13**	0.12*	
Rep (Env)	4	4634227*	2.86**	4.73	0.33	2773.55**	1125.41*	2.27**	1.62*	1.77*	0.48**	
Block (Env*Rep)	56	3047860	7.24	8.74	0.82	682.17*	348.67	0.23	0.18	0.16	0.03	
Hybrids	54	18768995**	43.61**	17.08**	1.53*	7784.87**	1619.82**	4.98**	1.54**	1.27**	0.06**	
GCA	10	62590853**	125.16*	50.03**	4.98*	33594.96**	5684.89**	13.50**	4.27**	3.53**	0.07*	
SCA	44	8809482**	25.11*	9.59	0.74	1918.94*	1073.30**	3.05**	0.92**	0.76**	0.06*	
Env x Hybrids	162	5697195**	6.09*	9.49	0.97	575.74*	271.98	0.57**	0.33	0.24*	0.03	
Env x GCA	30	6978883	6.51*	5.06	1.08	911.36	237.90	0.84	0.76	0.36	0.05	
Env x SCA	132	7798236	5.99*	10.50	0.95	969.13	279.73	0.88	0.58	0.35	0.03	
Residual	160	3454719	3.56	9.20	1.07	440.67	287.06	0.88	0.54	0.33	0.04	
GCA:SCA Ratio		0.93	0.91	0.91	0.93	0.97	0.91	0.90	0.90	0.90	0.72	

Legend: *, ** Significant at 0.05 and 0.01 probability levels, respectively; GY (grain yield); DTA (days to anthesis); DTS (days to silking); ASI (anthesis silking interval); PHT (plant height); EHT (ear height); EPP (numbers of ears per plant); PA (plant aspect); EA (ear aspect); HC (husk cover); LDS (leaf death score)

Table 3. GCA effects of 11 low-N and drought-tolerant maize inbred lines for grain yield and other agronomic traits under drought-stress and rainfed conditions

Parent	GY	DAT	DSK	ASI	PHT	EHT	PAS	EAS	HC	EPP	LDS
Drought-stress condition											
SMLW - 100	-307.06*	-1.62**	-1.60**	0.18*	-6.44*	-1.63	0.30**	0.13	0.14*	-0.02	0.32*
SMLW - 145	-128.19	-0.52*	-0.41	-0.02	-4.69	-4.20*	0.21**	0.21*	0.01	0.04	0.11
SMLW - 146	-105.10	0.12	0.09	0.05	-2.96	-1.44	0.01	-0.22*	0.09	0.04	0.05
SMLW - 156	273.72*	-0.09	-0.20	-0.07	-8.26*	-2.69	-0.03	-0.17	-0.22*	0.04	-0.38*
SMLW - 159	-137.03	0.65*	0.61*	0.04	-7.29*	-6.18**	-0.27**	-0.01	0.08	-0.07*	0.23
SMLW - 163	235.21*	0.59*	0.59*	-0.09	-15.16**	-3.95*	-0.11*	0.02	-0.11	0.03	-0.13
SMLW - 165	154.58	-0.20	-0.34	-0.18*	3.92	-3.25	-0.11*	-0.13	-0.09	0.01	-0.31*
SMLW - 169	-36.31	-0.30	-0.46	-0.25*	8.60*	7.87**	-0.27**	0.07	0.06	-0.01	0.09
SMLW - 24	188.14	0.97**	1.06**	0.14	7.45*	5.98**	-0.24**	0.04	-0.02	-0.04	0.03
SMLW - 99	-633.04**	0.11	0.24	0.18*	17.13**	6.76**	0.89**	-0.05	0.28**	-0.07*	0.44**
SMLW - 167	495.10**	0.30	0.41	0.03	7.70*	2.72	-0.38**	0.10	-0.22*	0.05*	-0.47**
Rainfed condition											
SMLW - 100	-472.76*	-0.06	-0.44	-0.10	2.46	1.63	-0.09	-0.07	-0.10*	-0.00	
SMLW - 145	573.11*	-0.19	-1.46**	-0.38**	7.85*	2.45	0.30**	0.10	0.10*	0.02	
SMLW - 146	-129.47	-0.47*	-0.05	-0.01	0.90	0.07	-0.26*	-0.13*	-0.16*	0.03*	
SMLW - 156	740.26**	0.50*	0.27	0.07	1.67	2.27	-0.55**	-0.30**	-0.26**	0.02	
SMLW - 159	1032.45**	0.97**	-0.04	-0.10	-12.73**	-0.43	-0.25*	-0.15*	-0.08	0.04	
SMLW - 163	581.54*	0.55**	-0.22	0.12	2.17	-4.50*	-0.42**	-0.17*	-0.16*	-0.02	
SMLW - 165	-631.41*	0.30	-0.28	0.13	1.32	-1.16	0.28**	0.15*	0.18*	-0.07**	
SMLW - 169	-1084.52**	-1.84**	0.14	0.07	-0.73	-0.76	0.50**	0.36**	0.23**	-0.03*	
SMLW - 24	-117.15	0.78**	-0.14	0.01	-51.79**	-5.19**	0.05	0.16*	0.05	0.01	
SMLW - 99	138.70	1.11**	1.90**	-0.06	41.00**	2.74*	-0.39**	-0.28**	-0.21**	0.02	
SMLW - 167	-630.75*	-1.66**	0.32	0.25*	7.88*	2.86*	0.83**	0.33**	0.39**	-0.02	

Legend: *, **, Significant at 0.05 and 0.01 probability levels, respectively; GY (grain yield); DSK (days to silking); ASI (anthesis silking interval); PHT (plant height); PAS (plant aspect); EAS (ear aspect); HC (husk cover); EPP (ear per plant); LDS (leaf death score).

Table 4. SCA effects for yield of 11 low-N and drought-tolerant maize inbred lines under drought-stress condition (above the diagonal) and rainfed condition (below the diagonal)

	SMLW-145	SMLW -146	SMLW-156	SMLW-159	SMLW-163	SMLW-165	SMLW-167	SMLW-169	SMLW-24	SMLW-99	SMLW-100
SMLW-145		-223.0	-621.2	-315.9	-618.4	195.5	778.6	-125.3	396.8	744.9	-211.8
SMLW -146	1419.5		-508.1	182.9	982.0*	-206.7	298.9	-512.9	-35.3	99.8	-77.0
SMLW-156	-798.9	1998.1*		933.0*	-569.1	-613.1	71.2	1377**	2.6	84.9	-157.2
SMLW-159	1394.3	1089.1	-2590.6**		545.5	-250.4	189.4	-261.9	-548.5	-233.9	-240.5
SMLW-163	-1657.9*	-699.8	-696.3	1099.8		97.2	-123.2	-411.4	22.9	380.9	-306.2
SMLW-165	318.7	138.7	388.5	794.8	1388.4		-917*	757.9	-478.9	-83.2	1498.0**
SMLW-167	-2568.5**	-577.6	1266.9	-68.9	2125.8*	-489.2		-247.7	75.7	-108.2	-17.9
SMLW-169	1327.8	-154.3	-386.6	725.2	-1278.5	-1755.2*	-1396.0		423.1	-1263.0**	265.2
SMLW-24	1567.1	-1496.9	501.2	-1141.8	-914.2	-1180.4	-313.3	225.5		636.5	-494.9
SMLW-99	-597.8	-157.2	912.8	529.3	853.0	-565.3	1070.5	146.4	203.7		-258.1
SMLW-100	-404.4	-1559.6	-595.2	-1831.2*	-220.2	960.9	950.2	2545.7**	2549.1**	-2395.4**	

Legend: *, **, Significant at 0.05 and 0.01 probability levels, respectively.

Flowering time was slightly delayed under drought conditions, with mean DAT and DSK of 64.5 and 68.0 days, respectively, compared to 57.6 and 60.3 days under rainfed conditions (Table 5). Under drought stress, SMLW-165 × SMLW-156 and SMLW-145 × SMLW-100 were the earliest flowering hybrids, reaching anthesis at approximately 58 days and silking at 62 days (Table 6). The latest-flowering hybrids under drought stress were SMLW-99 × SMLW-156 and SMLW-24 × SMLW-159, which reached anthesis at 68 days and silking at 71 days. Under rainfed conditions, SMLW-159 × SMLW-100 and SMLW-165 × SMLW-145 flowered earliest (55 DAT, 57 DSK), while SMLW-99 × SMLW-156 was the latest-flowering hybrid (62 DAT, 64 DSK). The shortest ASI were observed in SMLW-169 × SMLW-146 (2.5 days) under drought stress and SMLW-159 × SMLW-156 (1.9 days) under rainfed conditions. The longest ASI occurred in SMLW-169 × SMLW-145 under drought stress (4.4 days) and SMLW-163 × SMLW-156 under rainfed conditions (3.8 days).

Mean PHT and EHT were lower under drought-stressed conditions (130 cm and 72 cm, respectively) than under rainfed conditions (161 cm and 82 cm, respectively), Table 5. Under drought stress, hybrids SMLW-99 × SMLW-165, SMLW-99 × SMLW-163, and SMLW-145 × SMLW-100 were the tallest (>150 cm), with SMLW-145 × SMLW-100 also having the highest ear placement. Under rainfed conditions, SMLW-99 × SMLW-146 recorded the tallest plant and ear heights, while SMLW-24 × SMLW-159 had the lowest values for both traits. Generally, hybrids exhibited better ratings for PAS, EAS, HC and EPP under rainfed conditions than under drought stress. Hybrids with superior yield performance in each environment also had the best scores for these traits. For LDS, SMLW-167 × SMLW-163, SMLW-99 × SMLW-156, and SMLW-165 × SMLW-146 recorded the best ratings (scores of 2.4 to 2.7), indicating better stay-green ability. Conversely, SMLW-99 × SMLW-159 and SMLW-99 × SMLW-163 had the poorest LDS ratings (score: 6.6). Notably, most hybrids with better LDS ratings also had higher GY under drought stress.

Three multi-trait selection indices (SIP, I_N and BI) were used to identify hybrids tolerant to drought stress. Among the 55 diallel hybrids evaluated, the SIP index, with values ranging from –512.3 to 442.7, identified 19 hybrids (34.5 %) as drought-tolerant. The I_N index ranged from –15.7 to 24.8 and classified 25 hybrids (45.5 %) as tolerant to drought stress. The BI index, which had a range of –10.2 to 18.2, identified the highest number of drought-tolerant hybrids, totaling 28 (50.9 %) (Figure 1a). In terms of overlap between the selection indices, BI and IN jointly identified seven hybrids, I_N and SIP jointly identified one hybrid, and BI and SIP jointly identified three hybrids as drought-tolerant. All three indices unanimously identified 14 hybrids as drought-tolerant (Figure 1a), and these 14 hybrids are presented in Figure 1b. Among them, G19 (SMLW-165 × SMLW-146), G28 (SMLW-167 × SMLW-163), and G51 (SMLW-99 × SMLW-156) recorded the highest tolerance scores across all three indices.

Table 5. Means and ranges for grain yield and other traits of 55 diallel maize hybrids evaluated under drought-stressed and rainfed conditions at Mokwa and Ilora (2021- 2023)

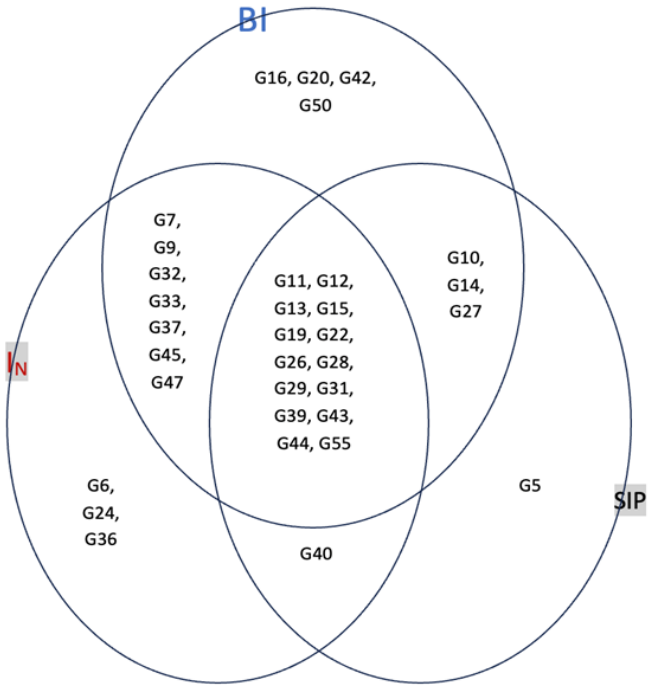
Trait	Drought-stress condition			Rainfed condition			Stress effect
	Min	Max	Mean	Min	Max	Mean	(%)
GY(kg/ha)	1036.8	4157.0	2271.0	2465.5	8733.0	5575.2	- 59.27
DAT (days)	58.2	68.0	64.5	54.8	61.9	57.6	+11.98
DSK (days)	61.3	71.3	68.0	57.4	64.4	60.3	+12.77
ASI (days)	2.5	4.4	3.5	1.9	3.8	2.8	+25.00
PHT (cm)	83.1	155.9	130.4	107.0	223.5	161.0	-19.01
EHT (cm)	36.6	105.4	72.2	48.2	134.1	82.0	-11.95
PAS (1 – 5)	2.3	4.8	3.8	1.5	4.9	3.1	+22.58
EAS (1 – 5)	2.6	4.7	3.8	2.1	4.1	3.0	+26.67
HC (1 – 5)	2.3	4.3	3.3	1.6	3.5	2.5	+32.00
EPP	0.6	1.1	0.8	0.6	1.1	0.9	-11.11
LDS (1 – 9)	2.4	6.6	5.3	–	–	–	–

Legend: GY (grain yield); DSK (days to silking); ASI (anthesis silking interval); PHT (plant height); PAS (plant aspect); EAS (ear aspect); HC (husk cover); EPP (ear per plant); LDS (leaf death score)

Table 6. Agronomic mean performance of maize hybrids under drought-stressed and rainfed conditions at Ilora and Mokwa, Nigeria (2021–2023)

Hybrid	GY		YRD (%)	DSK		ASI		PHT		PAS (1-5)		EAS (1-5)		HC (1-5)		EPP		LDS	TOLERANCE INDEX		
	DT	RF		DT	RF	DT	RF	DT	RF	DT	RF	DT	RF	DT	RF	DT	RF		SIP	BI	I_N
Drought Tolerant																					
SMLW - 159 x SMLW - 156	2945	6023	51.1	65.6	58.4	3.3	1.9	115	139	3.3	3.0	3.2	3.0	2.8	2.5	0.7	0.8	4.4	71	5.4	6.2
SMLW - 163 x SMLW - 100	2142	7058	69.7	67.3	59.4	2.9	2.3	91	146	3.8	2.0	4.2	2.6	3.1	2.0	0.9	0.8	5.1	37	2.2	2.6
SMLW - 163 x SMLW - 145	2573	6419	59.9	68.4	60.4	3.2	2.4	108	192	4.0	2.8	4.6	2.8	3.3	2.3	1.0	0.8	5.5	72	1.5	5.6
SMLW - 163 x SMLW - 156	2772	8733	68.3	68.1	61.9	3.3	3.8	107	163	3.5	1.7	3.6	2.4	3.0	1.9	0.8	0.8	5.3	349	5.2	4.1
SMLW - 165 x SMLW - 146	4126	6776	39.1	69.7	61.1	3.0	2.7	117	155	2.3	3.4	2.6	3.3	2.7	2.7	1.1	0.8	2.7	405	18.2	24.8
SMLW - 165 x SMLW - 163	3833	4192	8.6	70.5	60.2	3.6	3.7	120	180	3.4	2.9	3.5	2.7	2.6	2.4	0.9	0.8	4.0	112	6.7	14.7
SMLW - 167 x SMLW - 156	2582	6306	59.0	70.6	62.4	3.6	2.7	148	166	3.1	3.7	3.9	3.2	3.4	2.8	0.8	1.1	5.4	34	2.1	1.9
SMLW - 167 x SMLW - 163	4157	6603	37.0	67.8	60.6	3.6	3.2	135	164	2.6	3.2	2.8	3.1	2.3	2.5	1.1	0.8	2.4	355	15.4	23.0
SMLW - 167 x SMLW - 165	2435	6522	62.7	66.6	60.5	3.5	3.3	141	156	3.7	3.2	4.2	2.8	3.3	2.6	0.8	0.9	5.0	61	0.8	1.9
SMLW - 167 x SMLW - 24	2796	5985	53.3	69.8	60.3	3.3	2.5	114	157	4.2	3.2	4.6	3.0	3.4	2.6	0.8	1.0	5.4	137	0.1	4.7
SMLW - 169 x SMLW - 165	3515	4630	24.1	68.8	58.7	2.7	2.4	142	154	3.1	3.4	4.3	3.3	2.7	2.6	0.8	0.9	3.2	48	8.1	15.9
SMLW - 24 x SMLW - 156	2666	7416	64.0	70.4	60.3	2.9	3.1	143	129	3.6	1.5	3.6	2.3	3.3	1.7	0.7	0.8	5.6	178	3.5	2.2
SMLW - 24 x SMLW - 159	2704	5898	54.2	71.3	61.2	3.7	2.8	138	107	3.8	3.1	3.7	3.2	3.4	2.4	0.8	1.1	5.3	91	0.8	2.2
SMLW - 99 x SMLW - 156	3937	8642	54.4	70.8	64.4	2.8	2.6	131	205	2.8	1.6	2.9	2.1	2.6	1.9	1.0	0.9	2.7	443	16.4	21.5
SMLW - 156 x SMLW - 146	2773	3909	29.1	68.1	59.4	3.4	2.7	83	165	4.1	2.8	3.8	2.9	3.5	2.4	1.0	1.0	5.6	-108	0.7	5.6
SMLW - 159 x SMLW - 145	2552	5304	51.9	70.1	59.9	3.5	2.7	100	149	3.9	2.7	4.5	2.7	3.3	2.3	0.9	1.0	5.4	-25	0.0	3.8
SMLW - 167 x SMLW - 99	2583	5333	51.6	69.1	60.8	3.8	2.5	141	163	3.5	2.9	3.7	3.0	2.9	2.4	0.9	0.9	5.0	-94	1.9	4.0
SMLW - 169 x SMLW - 100	2695	3675	26.7	67.9	59.8	3.0	2.5	131	170	3.3	4.7	3.0	4.1	3.2	3.2	0.8	0.7	4.7	-164	4.8	6.1
SMLW - 169 x SMLW - 159	2345	3765	37.7	67.9	60.2	2.7	2.4	145	172	3.3	3.2	3.5	3.2	3.1	2.7	0.6	1.0	5.1	-297	1.7	0.8
SMLW - 24 x SMLW - 163	2533	4359	41.9	67.8	59.5	3.5	3.5	123	118	3.8	3.6	4.0	3.4	3.0	2.9	0.8	0.9	4.8	-49	0.0	2.9
SMLW - 24 x SMLW - 169	3002	4238	29.2	68.4	59.9	3.4	3.0	130	128	3.8	3.1	3.4	3.2	3.1	2.5	0.8	0.9	5.4	-13	1.9	4.9
SMLW - 24 x SMLW - 100	2432	5683	57.2	67.2	60.7	3.7	3.0	130	112	3.9	3.3	3.9	3.2	3.2	2.5	0.8	0.9	5.1	25	-0.4	0.9
SMLW - 159 x SMLW - 146	1640	8616	81.0	67.9	61.9	3.3	2.7	104	156	3.5	1.8	3.9	2.2	3.7	1.9	0.7	1.0	6.0	46	0.1	-6.1
SMLW - 163 x SMLW - 146	2016	8010	74.8	68.7	59.4	3.8	2.5	116	150	3.7	1.8	3.7	2.3	3.3	2.0	0.9	0.9	5.8	81	0.8	-2.3
SMLW - 167 x SMLW - 159	2648	6596	59.9	69.0	62.4	3.8	3.1	124	164	3.5	3.0	3.4	3.0	3.0	2.4	0.6	0.9	5.0	107	1.4	-0.1
SMLW - 156 x SMLW - 100	2323	7981	70.9	68.6	59.8	4.1	2.8	111	172	4.5	1.7	4.3	2.1	3.3	1.7	0.9	1.0	5.5	133	-1.6	-0.2
Non- Tolerant																					
SMLW - 99 x SMLW - 24	1037	5302	80.4	68.4	62.7	4.1	2.9	149	211	4.3	3.0	3.6	2.7	4.3	2.5	0.6	0.9	6.4	-428	-8.8	-15.7
SMLW - 167 x SMLW - 169	1661	2465	32.6	67.2	62.4	3.4	3.0	137	168	4.1	4.7	4.7	3.6	4.0	3.2	0.8	0.8	6.0	-458	-6.4	-4.6
SMLW - 99 x SMLW - 165	1266	4792	73.6	67.5	63.2	3.3	2.9	156	218	3.9	2.6	4.6	2.8	3.4	2.3	0.6	0.9	5.7	-473	-6.6	-10.0
SMLW - 145 x SMLW - 100	1416	4378	67.6	62.2	58.6	3.7	1.9	151	161	4.3	3.1	3.6	2.9	3.7	2.4	0.7	1.1	6.3	-477	-5.6	-8.9
SMLW - 99 x SMLW - 163	1225	3764	67.5	67.3	61.7	3.4	2.6	155	198	4.8	3.0	4.1	3.1	3.9	2.7	0.6	0.9	6.6	-512	-9.3	-12.4
Hybrid Check	3610	6897	47.7	65.3	59.7	3.8	2.4	140	155	3.3	3.0	3.0	3.0	2.9	2.4	0.8	0.9	4.7	307	6.7	9.2

Legend: DT (drought-stress condition), RF (rainfed condition), GY (grain yield); DSK (days to silking); ASI (anthesis silking interval); PHT (plant height); PAS (plant aspect); EAS (ear aspect); HC (husk cover); EPP (ear per plant); LDS (leaf death score); YRD (yield reduction); BI (IITA Base Index), I_N (Drought Selection Index), SIP (Selection Index Based on Trait Points)



Code	Hybrid
G10	SMLW - 159 x SMLW - 146
G11	SMLW - 159 x SMLW - 156
G12	SMLW - 163 x SMLW - 100
G13	SMLW - 163 x SMLW - 145
G14	SMLW - 163 x SMLW - 146
G15	SMLW - 163 x SMLW - 156
G16	SMLW - 163 x SMLW - 159
G19	SMLW - 165 x SMLW - 146
G20	SMLW - 165 x SMLW - 156
G22	SMLW - 165 x SMLW - 163
G24	SMLW - 167 x SMLW - 145
G26	SMLW - 167 x SMLW - 156
G27	SMLW - 167 x SMLW - 159
G28	SMLW - 167 x SMLW - 163
G29	SMLW - 167 x SMLW - 165
G31	SMLW - 167 x SMLW - 24
G32	SMLW - 167 x SMLW - 99
G33	SMLW - 169 x SMLW - 100
G36	SMLW - 169 x SMLW - 156
G37	SMLW - 169 x SMLW - 159
G39	SMLW - 169 x SMLW - 165
G40	SMLW - 24 x SMLW - 100
G42	SMLW - 24 x SMLW - 146
G43	SMLW - 24 x SMLW - 156
G44	SMLW - 24 x SMLW - 159
G45	SMLW - 24 x SMLW - 163
G47	SMLW - 24 x SMLW - 169
G5	SMLW - 156 x SMLW - 100
G50	SMLW - 99 x SMLW - 146
G51	SMLW - 99 x SMLW - 156
G6	SMLW - 156 x SMLW - 145
G7	SMLW - 156 x SMLW - 146
G9	SMLW - 159 x SMLW - 145

Figure 1a. Maize hybrids identified as drought-tolerant by IITA Base Index (BI), Drought Selection Index (I_N), and Selection Index based on Trait Points (SIP)

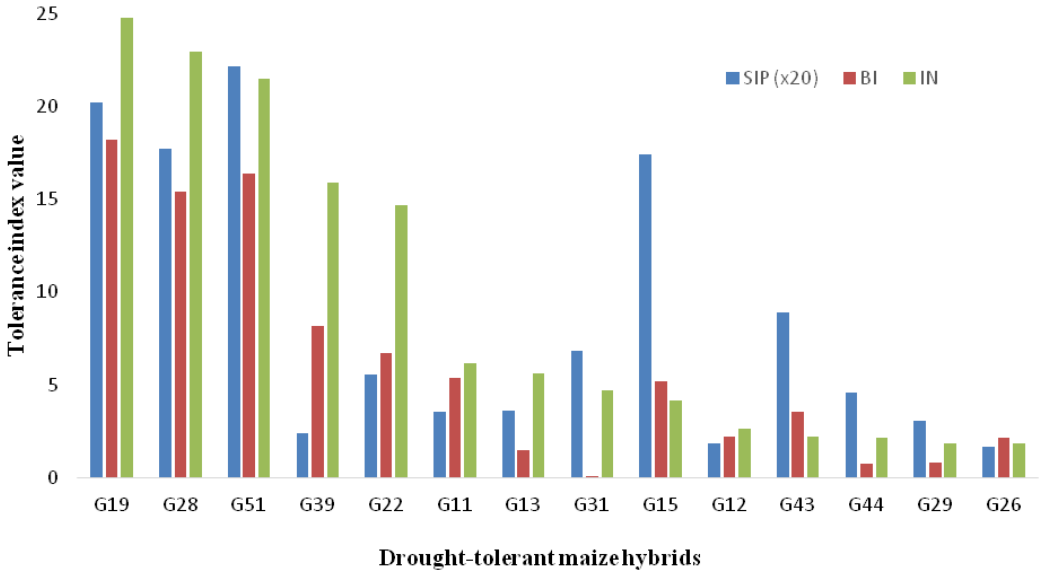
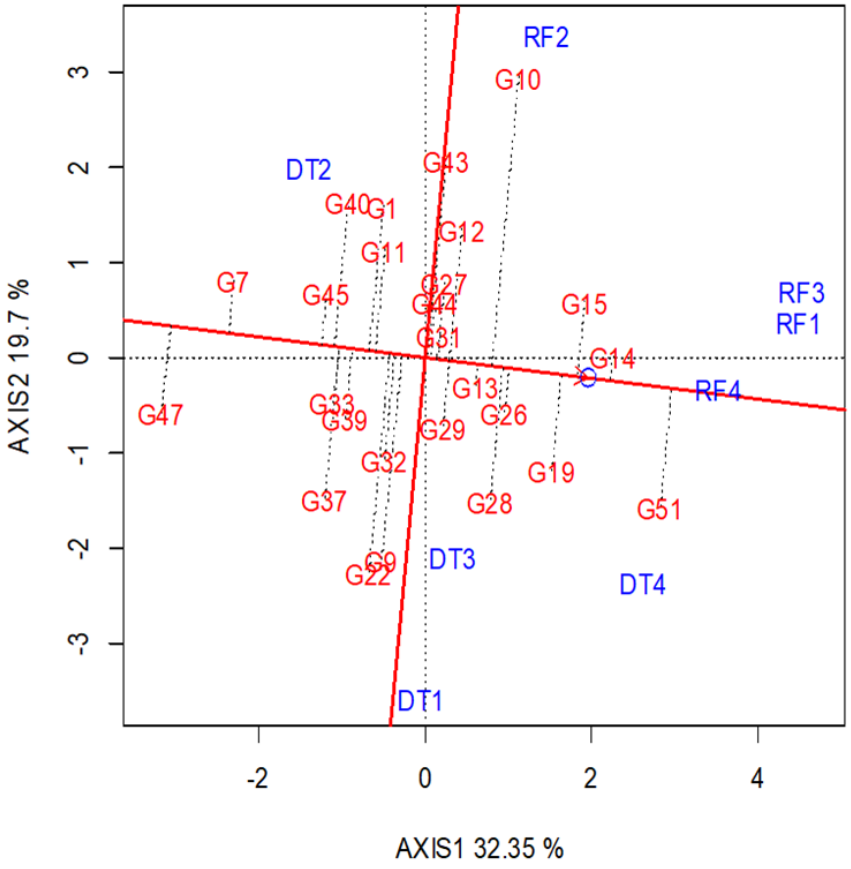


Figure 1b. Tolerance values of drought-tolerant hybrids commonly identified by BI, I_N, and SIP indices

Stability analysis of drought-tolerant hybrids across eight environments

The "mean vs. stability" view of the GGE biplot, generated using average GY data from 25 drought-tolerant hybrids (identified by at least two of the selection indices) and one hybrid check evaluated across eight test environments (Mokwa and Ilora) over the 2021-2023 cropping seasons, is presented in Figure 2. In the biplot, the single-arrowed line is the Average Tester Coordinate (ATC) abscissa, which represents the mean performance of the hybrids, with the arrow pointing toward higher mean GY. The line perpendicular to it and passing through the biplot origin is the ATC ordinate, which separates hybrids with above-average GY from those with below-average GY. Hybrids positioned to the right of the ATC ordinate exhibited above-average GY, whereas those to the left recorded below-average yields. The position of each hybrid's projection along the ATC abscissa, in the direction of the arrow, was used to rank mean GY. Stability was assessed from the perpendicular (dotted) line joining each hybrid to the ATC abscissa: hybrids located closer to the abscissa (shorter dotted lines) were considered more stable across environments, while those farther away were considered less stable. Based on these interpretations, the four highest-yielding drought-tolerant hybrids across all environments, in descending order of performance, were G51 (SMLW - 99 x SMLW - 156), G14 (SMLW - 163 x SMLW - 146), G15 (SMLW - 163 x SMLW - 156), and G19 (SMLW - 165 x SMLW - 146). Among these, G14 was the most stable hybrid, while the others also demonstrated moderate stability across environments.



Code	Hybrid
G10	SMLW - 159 x SMLW - 146
G11	SMLW - 159 x SMLW - 156
G12	SMLW - 163 x SMLW - 100
G13	SMLW - 163 x SMLW - 145
G14	SMLW - 163 x SMLW - 146
G15	SMLW - 163 x SMLW - 156
G19	SMLW - 165 x SMLW - 146
G22	SMLW - 165 x SMLW - 163
G26	SMLW - 167 x SMLW - 156
G27	SMLW - 167 x SMLW - 159
G28	SMLW - 167 x SMLW - 163
G29	SMLW - 167 x SMLW - 165
G31	SMLW - 167 x SMLW - 24
G32	SMLW - 167 x SMLW - 99
G33	SMLW - 169 x SMLW - 100
G37	SMLW - 169 x SMLW - 159
G39	SMLW - 169 x SMLW - 165
G40	SMLW - 24 x SMLW - 100
G43	SMLW - 24 x SMLW - 156
G44	SMLW - 24 x SMLW - 159
G45	SMLW - 24 x SMLW - 163
G47	SMLW - 24 x SMLW - 169
G51	SMLW - 99 x SMLW - 156
G7	SMLW - 156 x SMLW - 146
G9	SMLW - 159 x SMLW – 145
DT1	Mokwa drought stress 2022
DT2	Mokwa drought stress 2023
DT3	Ilora drought stress 2022
DT4	Ilora drought stress 2023
RF1	Mokwa rainfed 2022
RF2	Mokwa rainfed 2023
RF3	Ilora rainfed 2022
RF4	Ilora rainfed 2023

Figure 2. Entry/tester genotype and genotype × environment (GGE) biplot of drought-tolerant hybrids (identified by at least two Selection Indices) and check across drought-stressed and rainfed conditions in Mokwa and Ilora, Nigeria (2021- 2023)

DISCUSSION

The significant genotypic variations observed for all measured traits under both drought-stressed and rainfed conditions underscore the presence of appreciable genetic diversity among the evaluated maize hybrids. This diversity is important for effective selection and genetic improvement (Aboderin et al., 2023). The significant environmental effects observed for most traits under both conditions reflect the strong influence of environmental variability on phenotypic expression, consistent with previous reports by Aboderin et al. (2023), Bankole and Aboderin (2024) and Matongera et al. (2023). The non-significant genotype-by-environment interaction (GEI) effects for all traits under drought-stressed conditions indicate relatively stable hybrid performance across drought environments, implying that drought-tolerant hybrids can be selected with minimal interference from GEI. In contrast, under rainfed conditions, the significant GEI effects observed for grain yield and several other traits indicate differential hybrid responses across environments, which may complicate selection and necessitate multi-environment testing to identify hybrids with broad adaptability and consistent performance. These findings align with earlier studies that emphasized the importance of subjecting promising hybrids to multi-location evaluations to validate their stability and performance before commercial release (Aboderin et al., 2023; Bankole and Aboderin, 2024; Amegbor et al., 2023).

The significant general combining ability (GCA) and specific combining ability (SCA) effects observed for most traits under both growing conditions indicate that additive and non-additive gene actions contribute to the inheritance of these traits. However, the predominance of GCA over SCA mean squares for GY and most traits under both conditions suggests that additive gene action was more influential. This implies that the differences among the hybrids were largely attributable to the additive genetic effects of their parents. Therefore, population improvement through recurrent selection is feasible using these lines, capitalizing on the predominance of additive effects while still harnessing non-additive effects through hybridization (Aboderin et al., 2024a; Amegbor et al., 2023). These findings align with previous reports indicating that while both additive and non-additive gene actions contribute to trait inheritance under contrasting moisture conditions, additive effects tend to predominate (Amegbor et al., 2023; Adebayo et al., 2017; Obeng-Bio et al., 2019). The general absence of significant GCA × environment and SCA × environment interactions for most traits further indicates that the combining abilities of the parental lines were relatively stable across environments. For the hybrids, this means that their performance can be predicted reliably from the GCA of their parents across locations and seasons, so parents selected in one environment are likely to give consistent hybrid performance in others, reducing the need for extensive testing. Such genetic consistency is advantageous for breeding, as it allows for reliable selection of parents with favorable performance across diverse locations and seasons.

Given the significant combining ability effects, estimates of GCA and SCA were essential for assessing the breeding value of the lines. Some lines exhibited consistently favorable GCA effects across multiple traits, while others displayed contrasting combining ability. Most traits had predictive ratios exceeding 0.80 under drought-stressed and rainfed conditions, with only a few exceptions under drought stress. According to Baker (1978), a predictive ratio closer to one indicates a stronger influence of additive effects, enabling more accurate prediction of hybrid performance based on parental GCA. Among the tested lines, SMLW-156 demonstrated significant positive GCA effects for grain yield under both conditions, along with favorable negative GCA effects for traits associated with leaf death score (an indicator of stay-green capacity), plant aspect, ear aspect, and husk cover (a measure of grain protection). These attributes make it a valuable parent for hybrid development and for introgressing favorable alleles into breeding populations to improve yield and drought-stress tolerance. Interestingly, SMLW-156 was also identified as a good combiner for grain yield and flowering traits under low-N and optimal conditions in a separate study by Aboderin et al. (2024b).

Similarly, SMLW-163 showed significant positive GCA effects for grain yield under both conditions, in addition to favorable combining ability for plant height, ear height, plant aspect, ear aspect, and husk cover under rainfed conditions. These characteristics make it a valuable candidate for breeding programs targeting high yield, improved ear traits and reduced plant height to minimize lodging risk. SMLW-167, which showed significant positive GCA estimates for grain yield and ears per plant under drought stress, along with negative GCA estimate for leaf death score, is also a valuable resource for developing drought-tolerant hybrids. Lines such as SMLW-145 and SMLW-159, which showed positive GCA effects for grain yield under rainfed conditions but not under drought conditions, may be better suited for breeding hybrids for non-stressed environments. Inbred lines SMLW-100, SMLW-145, and SMLW-169 were the best combiners for flowering traits, suggesting their potential for breeding early-maturing varieties that can escape terminal drought (Aboderin et al., 2024a).

SCA effects, which primarily capture non-additive component of the total genetic variation, revealed specific hybrid combinations with superior performance. Most hybrid combinations with significant positive SCA effects for GY in

the study involved at least one parent with favorable GCA for grain yield, except for SMLW-169 × SMLW-100 and SMLW-24 × SMLW-100, both of which involved parents with negative GCA effects for grain yield. The high SCA effects in these exceptions could be due to dominance × dominance (non-allelic) interactions leading to overdominance, which, although non-fixable, can result in high-performing hybrids. Conversely, hybrids derived from good × poor general combiners may benefit from the favorable additive effects of the good parent and epistatic interactions involving the poor parent (Chigeza et al., 2014; Fasahat et al., 2016). The hybrids identified with significant SCA effects for GY under each condition represent valuable genetic combinations for enhancing yield potential under specific environments and should be prioritized for regional testing and further multi-location evaluation.

Furthermore, another main objective of this study was to identify maize hybrids that are high-yielding, drought-tolerant, and stable across diverse environmental conditions in Nigeria. The significant reduction in GY under drought stress highlights the susceptibility of maize hybrids to moisture deficit, consistent with previous findings from tropical maize breeding programs, where drought stress has been shown to cause substantial yield losses (Bankole et al., 2017; Bonkoungou et al., 2024; Oyekunle and Badu-Apraku, 2014). Beyond the direct yield penalties, drought stress also led to delayed flowering and compromized vegetative and reproductive vigor, factors that collectively contributed to yield reduction under stressed conditions.

Despite these negative effects, several hybrids demonstrated high yield performance under both drought-stressed and rainfed conditions, indicating the presence of genetic variability for drought resilience and yield potential. However, grain yield under drought stress alone is not a sufficient criterion to distinguish truly drought-tolerant genotypes. A hybrid may exhibit high yield not due to inherent tolerance, but because of escape or avoidance mechanisms, such as early-flowering or completing its reproductive cycle before the onset of severe drought (Malenica et al., 2021; Sayeed et al., 2021). To address this limitation, the present study employed three multi-trait selection indices (SIP, IN, and BI) that integrate secondary traits recognized as reliable indicators of true drought tolerance (Aboderin et al., 2024b; Oyekunle and Badu-Apraku, 2014). These traits are known to be heritable and consistently associated with yield under stress. Each index captures drought response from a different perspective, and their combined use allows for a more comprehensive assessment of hybrid performance, enabling cross-validation of selections and reducing the risk of advancing sub-optimal genotypes.

The indices differed slightly in the number of hybrids classified as drought-tolerant, with the BI index identifying the highest number, followed by IN and then SIP. Notably, all three indices unanimously identified 14 hybrids as drought-tolerant. Among these, SMLW-165 × SMLW-146, SMLW-167 × SMLW-163, and SMLW-99 × SMLW-156 recorded the highest yields under drought stress and achieved top tolerance scores across all three indices, confirming their status as the most drought-tolerant hybrids in this study.

Although the GEI effect for grain yield under drought stress was not significant, suggesting that selected drought-tolerant hybrids are likely to perform consistently under other drought-stressed environments, the significant GEI observed under rainfed conditions indicates inconsistent hybrid performance in non-stressed environments. For this purpose, a GGE biplot analysis was conducted considering only the 25 drought-tolerant hybrids identified by at least two selection indices. The GGE biplot analysis identified SMLW-99 × SMLW-156, SMLW-163 × SMLW-146, SMLW-163 × SMLW-156, and SMLW-165 × SMLW-146 as the four highest-yielding drought-tolerant hybrids based on mean performance across environments. Among these, SMLW-99 × SMLW-156 emerged as the most outstanding hybrid in this study, based on its superior mean yield under both drought-stressed and rainfed conditions, its high scores for drought tolerance across the multi-trait selection indices, and its moderate yield stability across environments. This hybrid was previously reported to be high-yielding and tolerant to low nitrogen (Aboderin et al., 2024b), making it an excellent candidate for on-farm trials to validate its yield consistency and stress resilience for potential release, especially in regions affected by both drought and low soil nitrogen. Similarly, the drought-tolerant hybrid, SMLW-163 × SMLW-156, which recorded the highest yield under rainfed conditions and maintained above-average yield performance across environments, may be better suited for regions with more reliable rainfall, given the significant yield reduction observed under drought stress. Based on their combining ability for grain yield, the parental lines SMLW-156 and SMLW-163 and SMLW-167 are recommended for introgression of favorable alleles and for population improvement through recurrent selection, with the aim of increasing grain yield and improving drought tolerance.

CONCLUSION

Significant genotypic variation was observed for all measured traits under both drought-stressed and rainfed conditions, indicating substantial genetic diversity among the evaluated hybrids. The inheritance of these traits was influenced by both additive and non-additive gene actions, with additive genetic effects being predominant. High

predictive ratios (> 0.8) observed for most traits under both research conditions suggest that the GCA effects of parental lines can be effectively used to predict hybrid performance. Among the low-nitrogen and drought-tolerant inbred lines evaluated, SMLW-156 and SMLW-163 emerged as outstanding general combiners for grain yield and key adaptive traits under both conditions, making them valuable sources of favorable alleles for population improvement and introgression into breeding populations, aimed at increasing grain yield and improving drought tolerance. Inbred lines SMLW-145 and SMLW-159, which showed good GCA effects for grain yield only under rainfed conditions, may be better suited for hybrid development targeted at favorable environments.

Fourteen hybrids were identified as drought-tolerant hybrids using three multi-trait selection indices (SIP, I_N, and BI). Among these, SMLW-99 × SMLW-156 and SMLW-163 × SMLW-156 emerged as the most outstanding hybrids. SMLW-99 × SMLW-156, based on its superior mean yield under drought-stressed and rainfed conditions, high tolerance scores across all selection indices, and moderate yield stability across environments, is recommended for cultivation in drought-prone areas. SMLW-163 × SMLW-156, which recorded the highest yield under rainfed conditions but experienced a substantial yield reduction under drought stress, is better suited for environments with high maize production potential.

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