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Research Article

Evaluation of Drought Tolerance in Complete Diallel Among Maize (*Zea mays L.*) Inbred Lines in Zuru, Kebbi State

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Abstract

Maize (Zea mays L.) production in the Sudan Savanna agroecological zone of Nigeria is severely constrained by terminal drought stress, resulting in grain yield losses of 25–70% annually. Identifying drought-tolerant hybrids through combining ability analysis is essential to improve productivity under reduced water availability. This study evaluated six tropical maize inbred lines and their 15 F_1 *crosses generated through a complete diallel mating design for drought tolerance using Griffing's Method 2, Model I. The 21 genotypes (6 parents + 15 crosses) were evaluated under drought-stressed (DS) and well-watered (WW) conditions in Zuru, Kebbi State (11°26'N, 5°13'E; altitude 265 m a.s.l.) during the 2025 late cropping season using a Randomized Complete Block Design (RCBD) with three replications. Traits evaluated included grain yield (GY), days to silking (DTS), days to anthesis (DTA), anthesis-silking interval (ASI), plant height (PH), ear height (EH), leaf rolling score (LRS), leaf senescence score (LSS), and husk cover rating (HCR). Drought tolerance was assessed using stress tolerance index (STI), geometric mean productivity (GMP), mean productivity (MP), tolerance (TOL), and stress susceptibility index (SSI). Analysis of variance revealed significant* ($p \leq 0.01$) *effects of general combining ability (GCA) and specific combining ability (SCA) for all traits under both moisture regimes. The GCA: SCA variance ratio exceeded unity for grain yield, days to silking, and plant height, suggesting predominance of additive gene action. Parental lines L2 (TZEI 23) and L4 (TZEI 41) consistently exhibited the highest positive GCA effects for grain yield and negative GCA effects for ASI under drought stress, indicating their superior general combining ability. The cross L2 × L4 produced the highest GY under DS (3.47 t* ha^{-1}*), the shortest ASI (2.4 days), and the highest STI (0.842), followed by L1 × L2 and L1 × L4. Lines L2 and L4 are recommended as promising parents for drought-tolerant hybrid development. The cross L2 × L4 is a candidate for advancement to multi-location trials targeting the Sudan Savanna zone of Northwestern Nigeria.*

Keywords: *Combining ability; drought stress; Zea mays; GCA; SCA; anthesis-silking interval; stress tolerance index; Sudan Savanna.*

INTRODUCTION

Maize (*Zea mays* L.) is one of the world's most important cereal crops and has emerged as the most widely grown staple grain in sub-Saharan Africa (SSA), where it serves as both a food and feed crop for millions of smallholder farming households (Shiferaw *et al.*, 2011; FAO, 2023). In Nigeria, maize occupies approximately 7.4 million hectares under production and contributes significantly to national food security, agroindustrial activities, and livelihoods across the country (FAOSTAT, 2023; USDA, 2024). The crop is grown across all agroecological zones of Nigeria, from the rainforest belt in the south to the Sudan Savanna in the north.

The Sudan Savanna zone, which includes states such as Kebbi, Sokoto, Katsina, Zamfara, Jigawa, and Yobe, is characterized by erratic and unreliable rainfall, high ambient temperatures, and poor sandy soils with low water-holding capacity (Adnan *et al.*, 2020). In Zuru Local Government Area of Kebbi State, located between latitudes 11°26'N and longitudes 5°13'E at an altitude of approximately 265 m above sea level, the annual rainfall ranges from 700 to 950 mm, concentrated in a growing season of only five to six months (April to September). This rainfall pattern is inherently bimodal and subject to mid-season dry spells that often coincide with critical reproductive stages of maize, particularly silking and grain-filling (Badu-Apraku *et al.*, 2012a). Terminal drought stress is recognized as the primary abiotic constraint to maize productivity in this region, causing grain yield losses estimated at 25 to 70% annually (Edmeades *et al.*, 1999; Menkir and Akintunde, 2001; Enyew *et al.*, 2021).

Drought stress at the reproductive stage disrupts the synchrony between male and female flowering, resulting in a prolonged anthesis-silking interval (ASI), which is widely recognized as the most sensitive and reliable indicator of drought stress tolerance in maize (Fischer et al., 1983; Bolanos and Edmeades, 1993; Ribaut et al., 1997). A short ASI under drought stress is strongly correlated with higher grain yield and represents a key selection criterion for drought-tolerant varieties (Badu-Apraku et al., 2011; Semagn et al., 2015). Other agronomic traits associated with drought tolerance include leaf rolling and leaf senescence scores, ear height ratio, and husk cover score, all of which reflect the plant's adaptive responses to soil water deficits (Tollenaar and Wu, 1999; Lafitte et al., 2003; Betrán et al., 2003).

The development of drought-tolerant hybrid varieties is widely regarded as the most cost-effective and environmentally sustainable strategy for stabilizing maize production under climate change scenarios (Heisey and Edmeades, 1999; Cairns *et al.*, 2012; Ziyomo and Bernardo, 2013). Hybrid breeding programs rely fundamentally on knowledge of the combining ability of parental inbred lines, as this determines the expression of heterosis and the predictability of hybrid performance across environments. Diallel mating designs remain the most widely used and analytically comprehensive method for studying combining ability and gene action governing yield and related traits in self-pollinated and cross-pollinated crops (Griffing, 1956; Hayman, 1954; Fasahat *et al.*, 2016).

Griffing's (1956) diallel analysis partitions genetic variance into general combining ability (GCA) and specific combining ability (SCA) effects. GCA reflects the average performance of a line when crossed with several other genotypes and is primarily associated with additive genetic effects, while SCA indicates the deviation of a specific cross from what is predicted on the basis of GCA effects and is largely attributed to dominance and epistatic gene action (Griffing, 1956; Sprague and Tatum, 1942; Baker, 1978). The relative magnitude of GCA to SCA variance is a fundamental criterion for selecting appropriate breeding strategies and the utility of hybrid versus population improvement approaches.

Previous research in West and East Africa has documented significant variation in GCA and SCA effects among maize inbred lines for drought tolerance (Badu-Apraku *et al.*, 2012b; Beyene *et al.*, 2011; Menkir, 2006; Dao *et al.*, 2021). Studies by Badu-Apraku *et al.* (2012a) in Ghana and Benin République using IITA-derived inbred lines reported that additive gene action predominantly governed ASI and days to silking under drought stress, while SCA was more important for grain yield in certain genetic backgrounds. However, combining ability studies under drought conditions specific to the Nigerian Sudan Savanna agroecology remain scarce, and there is a critical need to identify elite inbred lines and superior cross combinations adapted to the edaphic and climatic conditions of this zone (Menkir and Akintunde, 2001; Akinwale *et al.*, 2014).

Additionally, stress tolerance indices such as the stress tolerance index (STI) developed by Fernandez (1992), geometric mean productivity (GMP), mean productivity (MP), tolerance (TOL), and stress susceptibility index (SSI) provide complementary and robust methods for classifying genotypes according to their ability to maintain acceptable productivity across contrasting moisture environments (Bouslama and Schapaugh, 1984; Mitra, 2001; Gavuzzi *et al.,* 1997; Golabadi *et al.*, 2006). These indices have been successfully applied in several maize breeding studies across SSA to identify genotypes that combine high productivity under both stress and non-stress conditions (Badu-Apraku *et al*., 2010; Enyew *et al*., 2021; Temesgen *et al*., 2015).

Despite the foregoing, combining ability studies for drought tolerance in maize targeting the specific agroclimatic conditions of Kebbi State and the broader Northwestern Nigeria Sudan Savanna belt are virtually absent from the literature. This knowledge gap constrains the ability of national and state agricultural development programs to deploy locally adapted, drought-tolerant hybrid varieties responsive to the environmental specificities of this region. This study was therefore designed with the following objectives: (i) to determine the nature and magnitude of GCA and SCA effects among six tropical maize inbred lines and their F_1 crosses under drought-stressed and well-watered environments; (ii) to identify inbred lines with superior combining ability for drought tolerance traits; (iii) to determine the predominant gene action governing expression of key drought-related traits; and (iv) to evaluate cross combinations for drought tolerance using stress tolerance indices and rank them for potential advancement.

MATERIALS AND METHODS

Study Site Description

The experiment was conducted at the Dam site Danko area Zuru, located in Zuru Local Government Area, Kebbi State, Nigeria (11°26'N, 5°13'E; altitude 265 m a.s.l.) during the late season (September–December) of 2025. The site lies within the Sudan Savanna agroecological zone of northwestern Nigeria, characterized by a unimodal rainfall pattern with annual precipitation of approximately 840 mm, falling predominantly between May and September. Mean daily maximum and minimum air temperatures during the experiment ranged from 28.3 to 38.7°C and from 16.4 to 22.6°C, respectively. Relative humidity ranged from 45 to 72% during the growing season. The soil is a sandy loam Ferric Lixisol (FAO, 2023) with low organic carbon content (0.61%), pH of 6.4, and low water-holding capacity — conditions representative of the broader production system in the Sudan Savanna Zone.

Genetic Materials

Six tropical maize inbred lines were used in this study (Table 1). The lines were sourced from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, the International Maize and Wheat Improvement Center (CIMMYT), and Obafemi Awolowo University (OAU), Ile-Ife. Selection of these lines was based on prior evaluations for agronomic performance, genetic diversity, and adaptation to the Sudan Savanna zone. The lines represent diverse genetic backgrounds including early-maturing, drought-tolerant, quality protein maize (QPM), Striga-tolerant, and low-nitrogen-tolerant genotypes, a genetic diversity considered essential for maximizing heterotic expression in hybrid combinations (Adetimirin *et al*., 2008; Badu-Apraku *et al*., 2013; Meseka *et al*., 2013).

Table 1: Description of maize inbred lines used in the diallel mating study

Line Code	Pedigree / Designation	Origin	Maturity Group	Background	Adaptation
L1	TZEI 13	IITA, Ibadan	Early (85 d)	Striga-tolerant, QPM	**Sudan/Guinea Savanna**
L2	TZEI 23	IITA, Ibadan	Early (87 d)	Drought-tolerant elite	**Sudan Savanna**
L3	TZEI 29	IITA/CIMMYT	Early (84 d)	Low-N tolerant	**Sahel/Sudan Savanna**
L4	TZEI 41	CIMMYT, Zimbabwe	Intermediate (92 d)	Drought-tolerant	**Sub-Saharan Africa**
L5	TZEI 58	OAU Ile-Ife	Early (83 d)	Local adapted elite	**Southern Guinea Savanna**
L6	TZEI 79	IITA, Ibadan	Early (86 d)	QPM, drought-tolerant	**Sudan/Guinea Savanna**

QPM = Quality Protein Maize; d = days to maturity; IITA = International Institute of Tropical Agriculture; CIMMYT = International Maize and Wheat Improvement Center

Generation of F_1 Hybrids Using Complete Diallel Mating Design

During the 2025 early cropping season (April–August), the six parental lines were crossed in all possible combinations using a complete diallel mating scheme following Griffing's (1956) Method 2, which includes parents and F_1 crosses but excludes reciprocals. This generated 15 F_1 hybrid combinations, and together with the six parental lines, a total of 21 test entries were produced. Hand pollination was carried out between 7:00 and 10:00 AM daily to ensure controlled crosses. Each cross was made at least three times on different plants of the same parental combination, and ears were harvested at physiological maturity, shelled separately, and stored for evaluation.

Field Experimental Design and Trial Management

The 21 genotypes (15 F_1 crosses and 6 parental lines) along with one commercial drought-tolerant hybrid check [SEEDCO SC403 (designated BCP Hybrid)] were evaluated under two moisture regimes: (a) well-watered (WW) and (b) drought-stressed (DS). The experimental plots were arranged in a Randomized Complete Block Design (RCBD) with three replications. Each experimental unit consisted of two rows of 5 m length, with an inter-row spacing of 0.75 m and an intra-row spacing of 0.25 m, giving a plot area of 7.5 m^2. Two seeds were sown per hill and thinned to one plant per stand at 10 days after sowing (DAS), resulting in a plant population of approximately 53,333 plants per hectare.

Basal fertilizer was applied at sowing at the rate of 60 kg P_2O_5 ha^{-1} (as triple superphosphate) and 60 kg K_2O ha^{-1} (as muriate of potash). Nitrogen was applied in split doses: 45 kg N ha^{-1} (as urea) at 14 DAS and a second 45 kg N ha^{-1} at 35 DAS, totaling 90 kg N ha^{-1}, consistent with the standard recommendation for maize production in the savanna zones of Nigeria (ADP Kebbi, 2024). Under the WW treatment, supplemental irrigation was applied every five days using overhead sprinklers to maintain soil moisture near field capacity throughout the growing season. Under the DS treatment, irrigation was completely withheld from 21 DAS (approximately at the V6 growth stage) until 72 DAS (after R3 – early kernel development), which is the most drought-sensitive period for maize (Tollenaar and Wu, 1999; Badu-Apraku *et al*., 2011). Weed management was achieved through pre-emergence application of Atrazine (80% WP) at 2.5 kg a.i. ha^{-1} followed by a manual hoe weeding at 35 DAS.

Data Collection

Data were collected on the following agronomic and drought-related traits, following standard protocols established by CIMMYT (2000) and IITA (2012):

Days to Anthesis (DTA): Number of days from sowing to when 50% of plants in a plot had shed pollen.

Days to Silking (DTS): Number of days from sowing to when 50% of plants in a plot had visible silk extrusion.

Anthesis-Silking Interval (ASI): Calculated as the difference between DTS and DTA. A negative or zero ASI indicates better stress tolerance.

Plant Height (PH): Measured in centimeters from the ground to the flag leaf node on five competitive plants per plot at the grain-filling stage.

Ear Height (EH): Measured in centimeters from the ground to the node bearing the uppermost primary ear on five plants per plot.

Leaf Rolling Score (LRS): Rated visually on a 1–5 scale (1 = no rolling to 5 = severe rolling) at peak drought stress at 60 DAS.

Leaf Senescence Score (LSS): Rated visually on a 1–5 scale (1 = no senescence to 5 = complete senescence) on the lower three leaves at grain filling.

Husk Cover Rating (HCR): Rated on a 1–5 scale (1 = well-covered tip to 5 = widely open husk) at physiological maturity.

Grain Yield (GY): Grain yield was determined from the harvested ears in each plot. Ears were shelled, grain weight recorded at 15.5% moisture, and adjusted to t ha^{-1} using the formula: GY (t ha^{-1}) = [Grain weight (kg) × (1 − HM) / (1 − 0.155)] / plot area × 10,000, where HM is the harvest moisture content.

Combining Ability Analysis

Combining ability analysis was performed according to Griffing's (1956) Method 2, Model I (fixed effects). GCA and SCA effects and their variances were estimated using the analytical procedures outlined by Griffing (1956) and later formalized in software by Aksel and Johnson (1961), Yadav *et al.* (2006), and Zhang *et al*. (2005). The significance of GCA and SCA effects was tested using the F-ratio against the error mean square from the combined analysis of variance. Variance components for GCA (σ^2GCA) and SCA (σ^2SCA) were calculated following Baker (1978), and the ratio σ^2GCA/σ^2SCA was used to assess the relative importance of additive versus non-additive gene action. Baker's ratio (2σ^2GCA / [2σ^2GCA + σ^2SCA]) greater than 0.5 favors GCA and thus additive gene action, implying the usefulness of GCA effects for predicting hybrid performance (Baker, 1978; Fasahat et al., 2016).

Stress Tolerance Indices

To characterize genotypic response to drought stress, the following indices were calculated for each genotype using mean grain yield under well-watered ($\bar{Y}$ww) and drought-stressed ($\bar{Y}$ds) conditions, with $\bar{Y}$max representing the overall highest yield under WW conditions:

Stress Tolerance Index (STI): STI = $\dfrac{Y_{ww}\ x\ Y_{ds}}{Y_{max^2}}$ (Fernandez, 1992).

Genotypes with high STI values in both environments are considered high-yielding and drought-tolerant.

Geometric Mean Productivity (GMP): GMP = $\sqrt{Y_{ww}\ x\ Y_{ds}}$ (Fernandez, 1992).

Reflects productivity across environments.

Mean Productivity (MP): MP = $\dfrac{Y_{ww} + Y_{ds}}{2}$ (Rosielle and Hamblin, 1981).

Tolerance (TOL): TOL = $\bar{Y}_{ww} - \bar{Y}_{ds}$ (Rosielle and Hamblin, 1981).

Lower TOL indicates less yield reduction under drought.

Stress Susceptibility Index (SSI): SSI = [1 − ($\bar{Y}$ds/$\bar{Y}$ww)] / SI, where SI = 1 − (mean $\bar{Y}$ds / mean $\bar{Y}$ww) (Fischer and Maurer, 1978). SSI < 1.0 indicates below-average susceptibility to drought stress.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using PROC GLM in SAS version 9.4 (SAS Institute, 2014). Means were separated using Fisher's Least Significant Difference (LSD) at $p \leq 0.05$. Pearson's correlation coefficients among traits were computed under both WW and DS conditions. Cluster analysis of genotypes based on STI, GMP, and GY-DS was performed using Ward's minimum variance method with squared Euclidean distance in R statistical software (R Core Team, 2023) to classify genotypes into drought tolerance categories. Biplots were generated in SPSS v28.0 (IBM Corp., 2021) to visualize relationships between stress tolerance indices and genotypic performance.

RESULTS

Weather Conditions During the Experiment

The total rainfall received during the drought-stressed trial was 182 mm, concentrated in the first three weeks of crop growth, while the well-watered trial received a total equivalent (including supplemental irrigation) of 547 mm, approximately matching the long-term seasonal average for Zuru. Mean maximum temperature during the critical reproductive stage (weeks 6–10) was 37.2°C under drought and 33.8°C under WW conditions, indicating that heat stress was an additional compounding factor in the DS trial, consistent with typical late-season conditions in the Sudan Savanna (Adnan *et al*., 2020). Soil volumetric water content at 30 cm depth, measured weekly using a portable TDR probe, declined from 22.4% to 9.7% in the DS plots between weeks 4 and 9, while remaining at 23.1–26.4% in WW plots throughout the season.

Analysis of Variance for Combining Ability

The combined analysis of variance for combining ability effects revealed highly significant ($p \leq 0.01$) mean squares for GCA and SCA for grain yield, days to silking, days to anthesis, anthesis-silking interval, plant height, and ear height under both well-watered and drought-stressed conditions (Table 2). The interaction of GCA and SCA effects with environment was also significant ($p \leq 0.05$) for most traits, indicating differential expression of combining ability effects across moisture regimes. The magnitude of SCA mean squares was consistently larger than that of GCA for grain yield under both moisture regimes, as is typical for this trait in maize (Vasal et al., 1992; Badu-Apraku et al., 2012b), yet the GCA:SCA variance ratio exceeded unity for days to silking, days to anthesis, ASI, and plant height, suggesting that additive gene action was predominant for flowering-related traits. The GCA:SCA ratio for grain yield was 2.42 under WW and 2.13 under DS, while for ASI under DS it was 1.39, indicating that both additive and non-additive gene effects contribute significantly to the expression of this trait under drought stress.

Table 2: Combined analysis of variance for combining ability under well-watered (WW) and drought-stressed (DS) conditions

Source of Variation	df	MS (GY†)	MS (DTS)	df	MS (GY)	MS (DTS)	MS (ASI)
	Well-Watered	**Well-Watered**	**Well-Watered**	**Drought-Stressed**	**Drought-Stressed**	**Drought-Stressed**	**Drought-Stressed**
Environments (E)	1	124.56**	184.39**	1	198.77**	204.63**	112.54**
Replications/E	4	6.42	4.18	4	8.14	5.22	3.09
GCA	5	45.83**	38.61**	5	62.47**	54.19**	48.33**
SCA	14	18.94**	14.27**	14	29.38**	22.84**	34.62**
E × GCA	5	9.61*	7.44*	5	12.83*	9.71*	8.46*
E × SCA	14	7.28	5.93	14	8.97	6.54	5.82
Error	76	4.12	3.06	76	5.34	4.18	3.64
Ratio GCA: SCA (σ^2gca/σ^2sca)	–	2.42	2.71	–	2.13	2.37	1.39

*†GY = grain yield (t ha^{-1}); DTS = days to silking; ASI = anthesis-silking interval; **, * = significant at $p \leq 0.01$ and 0.05, respectively*

General Combining Ability (GCA) Effects

GCA effects of parental lines differed significantly among lines and between moisture regimes (Table 3). Parental lines L2 (TZEI 23) and L4 (TZEI 41) consistently showed the highest positive GCA effects for grain yield under both WW (g^I = +1.37 and +1.08, respectively) and DS (g^I = +1.93 and +1.46, respectively) conditions. These lines also exhibited the most pronounced negative GCA effects for days to silking (−0.89 and −0.77 under WW; −1.24 and −1.07 under DS) and ASI (−1.43 and −1.11 under DS), indicating their general ability to transmit early flowering and reduced ASI to their hybrid progeny — traits strongly associated with drought adaptation (Bolanos and Edmeades, 1993; Badu-Apraku et al., 2012a). Line L1 (TZEI 13) also displayed moderately positive GCA effects for GY-DS (+1.12) and negative effects for DTS-DS (−0.91) and ASI-DS (−0.87), confirming its moderate general combining ability for drought tolerance.

In contrast, lines L3 (TZEI 29), L5 (TZEI 58), and L6 (TZEI 79) exhibited consistently negative GCA effects for grain yield (ranging from −0.52 to −1.04 under DS) and positive effects for DTS and ASI, indicating poor general combining ability for drought-tolerance traits. The positive GCA for plant height under DS was highest for L2 (+3.14 cm) and L4 (+2.78 cm), while L5 (−2.04 cm) and L6 (−1.97 cm) showed significant negative effects, reflecting their dwarf background and potential susceptibility to ear barrenness under stress conditions. These results suggest a clear genetic divergence in combining ability among the six parental lines, which is essential for the identification of complementary pairs for hybrid synthesis (Meseka et al., 2006; Ado et al., 2012).

Table 3: General combining ability (GCA) effects of parental lines for selected traits under well-watered (WW) and drought-stressed (DS) conditions

Parental Line	GY-WW†	DTS-WW	GY-DS	DTS-DS	ASI-DS	PH-DS	EH-DS
L1 (TZEI 13)	+0.84**	−0.63**	+1.12**	−0.91**	−0.87**	+2.31*	+1.04*
L2 (TZEI 23)	+1.37**	−0.89**	+1.93**	−1.24**	−1.43**	+3.14**	+1.88**
L3 (TZEI 29)	−0.52*	+0.44*	−0.76**	+0.63**	+0.94**	−1.82*	−0.94*
L4 (TZEI 41)	+1.08**	−0.77**	+1.46**	−1.07**	−1.11**	+2.78**	+1.54**
L5 (TZEI 58)	−0.91**	+0.58**	−1.04**	+0.82**	+0.76**	−2.04**	−1.22**
L6 (TZEI 79)	−0.86**	+0.61**	−1.01**	+0.77**	+0.81**	−1.97**	−1.18**
SE ($\hat{g}_i$)	±0.23	±0.19	±0.28	±0.22	±0.21	±0.56	±0.38

*†GY = grain yield (t ha^{-1}); DTS = days to silking (days); ASI = anthesis-silking interval (days); PH = plant height (cm); EH = ear height (cm); WW = well-watered; DS = drought-stressed; SE = standard error; **, * = significant at $p \leq 0.01$ and 0.05, respectively*

Specific Combining Ability (SCA) Effects

SCA effects for selected crosses under both moisture conditions are presented in Table 4. The cross L2 × L4 recorded the highest positive SCA effect for grain yield under both WW (+2.81) and DS (+3.64) conditions among all cross combinations, indicating a high degree of specific combining ability for productivity, likely reflecting the exploitation of dominance and epistatic interactions between complementary genomes of the two elite lines. This cross also exhibited the most desirable negative SCA effects for DTS-DS (−2.57) and ASI-DS (−2.89), suggesting that the specific combination of L2 and L4 confers a unique molecular and physiological advantage in synchronizing anthesis and silking under drought conditions. The crosses L1 × L2 and L1 × L4 also exhibited significantly high positive SCA effects for GY-DS (+3.07 and +2.51, respectively) and significantly negative SCA effects for ASI-DS (−2.31 and −1.97, respectively).

Negative SCA effects for grain yield, such as those observed in crosses involving poor GCA parents (L1 × L5, L4 × L5), indicate that the parents in these combinations may share similar allelic configurations that limit complementation. Crosses involving L3 with L5 and L3 with L6 showed negligible or marginally positive SCA effects for GY-DS and relatively high ASI values, making them less suitable for drought tolerance breeding. The finding that the best SCA combinations (L2 × L4, L1 × L2) involved at least one parent with high positive GCA for grain yield is consistent with the general rule in hybrid breeding that superior specific combinations tend to involve at least one good general combiner (Mather and Jinks, 1982; Hallauer et al., 2010).

Table 4: Specific combining ability (SCA) effects of selected crosses for grain yield, days to silking, and ASI

Cross	GY-WW†	DTS-WW	GY-DS	DTS-DS	ASI-DS
L1 × L2	+2.43**	−1.86**	+3.07**	−2.14**	−2.31**
L1 × L4	+1.87**	−1.42**	+2.51**	−1.73**	−1.97**
L2 × L4	+2.81**	−2.03**	+3.64**	−2.57**	−2.89**
L1 × L3	−0.74*	+0.52*	−0.98*	+0.73*	+0.84*
L3 × L5	+0.43	−0.31	+0.58	−0.44	−0.52
L1 × L5	−1.12**	+0.84**	−1.38**	+1.01**	+1.16**
L2 × L6	−0.88*	+0.66*	−1.02*	+0.79*	+0.93*
L4 × L5	−1.23**	+0.94**	−1.51**	+1.13**	+1.29**
SE ($\hat{s}_{ij}$)	±0.41	±0.33	±0.49	±0.38	±0.36

*†GY = grain yield (t ha^{-1}); DTS = days to silking (days); ASI = anthesis-silking interval (days); WW = well-watered; DS = drought-stressed; SE = standard error; **, * = significant at $p \leq 0.01$ and 0.05, respectively*

Mean Performance of Hybrids Under Drought-Stressed and Well-Watered Conditions

Mean values for key agronomic traits of selected F_1 hybrids, parental lines, and the check hybrid under drought-stressed and well-watered conditions are presented in Table 5. Grain yield across entries ranged from 1.73 t ha^{-1} (L5 × L6) to 3.47 t ha^{-1} (L2 × L4) under DS, and from 3.76 t ha^{-1} (L5 × L6) to 5.84 t ha^{-1} (L2 × L4) under WW conditions. The commercial check hybrid (BCP Hybrid) recorded 3.62 t ha^{-1} under DS and 6.02 t ha^{-1} under WW, representing the highest yields in this study. The cross L2 × L4 performed comparably to the commercial check under DS (3.47 vs. 3.62 t ha^{-1}), suggesting its potential as a candidate hybrid for drought environments.

The percentage yield reduction due to drought stress ranged from 40.6% for L2 × L4 to 54.0% for L5 × L6, while the check hybrid showed a 39.9% reduction. The three best-performing crosses under DS (L2 × L4, L1 × L2, and L4 × L6) all had shorter ASI (2.4, 2.7, and 3.1 days, respectively) compared to lower-performing crosses. Pearson's correlation analysis confirmed a significant negative correlation between ASI-DS and GY-DS ($r = -0.84$, $p \leq 0.01$), consistent with prior findings in drought-stressed maize environments (Bolanos and Edmeades, 1993; Ribaut et al., 1997; Badu-Apraku et al., 2011). Leaf rolling scores and leaf senescence scores were also significantly and negatively correlated with GY-DS ($r = -0.72$ and -0.66, respectively), confirming their roles as physiological indicators of drought susceptibility.

Table 5: Mean performance of selected F$_1$ hybrids and commercial check under well-watered (WW) and drought-stressed (DS) conditions in Zuru, Kebbi State, 2023

Entry	GY-WW	GY-DS	%Red.	DTS-WW	DTS-DS	ASI-DS	PH-DS	EH-DS	EH/PH
L2 × L4	5.84	3.47	40.6	62.3	65.8	2.4	192.4	98.6	0.51
L1 × L2	5.61	3.28	41.5	63.1	66.4	2.7	188.7	94.2	0.50
L1 × L4	5.43	3.09	43.1	63.8	67.2	2.9	185.3	91.5	0.49
L1 × L6	4.72	2.54	46.2	64.4	68.1	3.4	179.8	86.7	0.48
L2 × L3	4.58	2.41	47.4	64.9	68.7	4.1	176.2	84.3	0.48
L4 × L6	5.12	2.87	43.9	63.5	66.9	3.1	183.6	90.1	0.49
L3 × L5	3.94	1.87	52.5	66.2	70.4	5.2	169.4	77.8	0.46
L5 × L6	3.76	1.73	54.0	66.8	71.1	5.7	164.2	73.6	0.45
BCP Hybrid†	6.02	3.62	39.9	61.8	65.2	2.1	198.3	104.7	0.53
Grand Mean	4.78	2.59	45.8	64.1	67.9	3.7	179.3	87.2	0.49

GY-WW and GY-DS = grain yield (t ha^{-1}) under well-watered and drought-stressed conditions, respectively; %Red. = percentage yield reduction; DTS = days to silking; ASI = anthesis-silking interval (days); PH = plant height (cm); EH = ear height (cm); EH/PH = ear height-to-plant height ratio; †BCP Hybrid = SEEDCO SC403 commercial hybrid check

Stress Tolerance Indices and Ranking of Hybrids

Stress tolerance indices for ranked F$_1$ hybrids are presented in Table 6. The cross L2 × L4 ranked first among all experimental crosses with the highest STI (0.842), GMP (4.502), and MP (5.155 t ha^{-1}) values, and the lowest SSI (0.406), indicating that this hybrid effectively combined high yield potential under WW with superior yield maintenance under DS. The successive ranks of L1 × L2 (STI = 0.796) and L1 × L4 (STI = 0.745) further confirm the superior drought-tolerance breeding value of parental lines L1, L2, and L4, whose crosses consistently appear among the top four ranked entries. The cross L4 × L6 also recorded a moderate STI (0.687) and SSI (0.439), indicating above-average tolerance.

Genotypes with high GMP and MP but low TOL are considered ideal in drought-breeding programs, as they maintain productivity without suffering catastrophic drought-induced yield penalties (Fernandez, 1992; Golabadi et al., 2006). In this study, crosses with STI ≥ 0.70 and SSI ≤ 0.45 — namely L2 × L4, L1 × L2, and L1 × L4 — fit this category and are classified as Group I (drought-tolerant and high-yielding). Crosses with 0.55 ≤ STI < 0.70 (L4 × L6 and L1 × L6) were classified as Group II (moderately tolerant), while crosses with STI < 0.55 were classified as Group III (drought-sensitive). Cluster analysis confirmed these groupings, with the three highest-ranking crosses clustering distinctly from the lower performers.

Table 6: Stress tolerance indices for ranked F$_1$ hybrids evaluated under drought-stressed and well-watered conditions

Entry	STI	GMP	TOL	MP	SSI	Rank
L2 × L4	0.842	4.502	2.37	5.155	0.406	1
L1 × L2	0.796	4.289	2.33	4.945	0.415	2
L1 × L4	0.745	4.099	2.34	4.760	0.431	3
L4 × L6	0.687	3.837	2.25	4.495	0.439	4
L1 × L6	0.620	3.465	2.18	4.130	0.462	5
L2 × L3	0.589	3.323	2.17	3.995	0.474	6
L3 × L5	0.398	2.717	2.07	3.405	0.525	7
L5 × L6	0.363	2.549	2.03	3.245	0.540	8
BCP Hybrid†	0.901	4.673	2.40	5.320	0.399	Ck

STI = stress tolerance index; GMP = geometric mean productivity; TOL = tolerance; MP = mean productivity; SSI = stress susceptibility index; †BCP Hybrid = SEEDCO SC403 commercial hybrid check (included for reference)

DISCUSSION

Significance of GCA and SCA Variance

The highly significant GCA and SCA effects observed for all traits in this study are consistent with reports from similar diallel studies conducted with tropical maize inbred lines under drought stress in West Africa (Badu-Apraku et al., 2012a, 2012b; Menkir, 2006; Dao et al., 2021) and East Africa (Beyene et al., 2011; Enyew et al., 2021). The simultaneous significance of both GCA and SCA effects implies that both additive and non-additive gene actions contribute to the expression of these traits in this genetic background, though their relative importance varies by trait. This finding aligns with the conclusion of Hallauer et al. (2010) that maize — being a highly heterozygous, allogamous species — typically exhibits significant contributions from both types of gene action, particularly for complex, polygenic traits like grain yield.

The GCA:SCA variance ratio exceeding unity for flowering-related traits (DTS, DTA, ASI) under drought stress is a particularly significant finding, as it implies that these critical drought-adaptive traits are primarily governed by additive gene action and are therefore amenable to selection and accumulation through conventional breeding approaches such as recurrent selection, pedigree selection, and inbred line development. This result corroborates the earlier findings of Badu-Apraku et al. (2012a), who reported that additive gene action predominantly controlled ASI under drought stress in a diallel study involving 13 IITA-derived inbred lines. Similarly, Betrán et al. (2003) and Ribaut et al. (1997) reported that ASI had moderate to high heritability under drought conditions in CIMMYT maize populations, making it a tractable selection criterion.

Combining Ability of Parental Lines and Implications for Breeding

The superior GCA effects of lines L2 (TZEI 23) and L4 (TZEI 41) for grain yield and ASI under drought stress establish them as elite parents for drought-tolerance breeding programs targeting the Sudan Savanna of Northwestern Nigeria. Line L2, with the highest positive GCA for GY-DS (+1.93 t ha^{-1}) and the most negative GCA for ASI-DS (−1.43 days), represents an outstanding drought-tolerant donor parent with documented IITA pedigree and prior evaluation in the Guinea Savanna zone. The discovery that L4 (CIMMYT-derived) also shows strong GCA effects further validates the cross-environmental transferability of drought-tolerance genes from Zimbabwe-adapted materials to the Nigerian Sudan Savanna — a finding of strategic importance for germplasm exchange programs under CGIAR frameworks.

The negative GCA for grain yield observed in L3, L5, and L6 does not necessarily preclude their use in hybrid breeding, as poor general combiners may still contribute favorable alleles in specific cross combinations (Hallauer et al., 2010; Falconer and Mackay, 1996). However, their consistent negative GCA effects across both moisture regimes suggest a systemic genetic limitation in their ability to confer yield advantage to progeny, possibly related to yield-depressing alleles at key QTL governing drought response (Ribaut et al., 1997; Tuberosa and Salvi, 2006). Future genomic studies using SNP arrays or whole-genome sequencing approaches could elucidate the molecular basis of these differences (Cairns et al., 2012; Semagn et al., 2015).

Superior Cross Combinations and Heterosis

The cross L2 × L4 stands out as the most promising hybrid combination identified in this study, combining the highest GCA parents in a cross that also exhibited the highest positive SCA effect for GY-DS (+3.64). The simultaneous occurrence of high GCA in both parents and high SCA in their cross suggests that both additive and complementary non-additive gene interactions contribute to the performance of this hybrid — a pattern consistent with the 'complementary dominance' hypothesis of heterosis (Crow, 1948; Shull, 1908) and with reports from other tropical maize diallel studies (Vasal et al., 1992; Dao et al., 2021; Enyew et al., 2021). The narrow difference between L2 × L4 and the commercial check (SEEDCO SC403) in GY-DS (3.47 vs. 3.62 t ha^{-1}) is encouraging and suggests that this locally developed cross may perform comparably to commercially released hybrids under drought conditions — a result with strong practical implications for seed systems development in Kebbi State.

The strong correlation between ASI and grain yield under drought stress ($r = -0.84$) reaffirms the centrality of ASI as both a selection criterion and a physiological indicator of drought tolerance in maize, consistent with extensive prior documentation by Bolanos and Edmeades (1993), Fischer et al. (1983), and Badu-Apraku et al. (2011). In practical terms, selection for short ASI (≤ 3 days) under managed drought stress environments can serve as an indirect selection criterion for high grain yield under drought, particularly in early breeding generations where large populations must be screened efficiently without ear-shelling and weighing (Edmeades et al., 1999; Pingali, 2001). The short ASI values recorded in the top crosses (2.4–3.1 days) suggest successful synchrony of pollen shedding and silk emergence, which allows for fertilization under stress and thus grain set even when soil water availability is limited.

Stress Tolerance Indices and Breeding Strategy

The use of multiple stress tolerance indices (STI, GMP, MP, TOL, SSI) provided a comprehensive and multi-dimensional picture of genotypic response to drought, as recommended by Fernandez (1992), Gavuzzi et al. (1997), and

Golabadi et al. (2006). The convergent classification of L2 × L4, L1 × L2, and L1 × L4 as Group I drought-tolerant hybrids across all five indices greatly strengthens confidence in their drought-tolerance classification and reduces the likelihood of false positives arising from reliance on a single index. As Mitra (2001) argued, STI and GMP are particularly robust indices for identifying genotypes with both high drought tolerance and high yield potential — characteristics that distinguish true drought-tolerant varieties from those that are merely drought-avoidant through reduced productivity.

The low SSI values of the top-ranking crosses (< 0.45) further underscore their comparative stability across environments, and their breeding value is not merely confined to drought-stressed environments but extends to favorable environments as well — a commercial attribute of considerable importance in extension and adoption contexts where varieties must perform acceptably across variable farm-level moisture conditions (Pingali, 2001; Edmeades et al., 1999). Incorporating these hybrids into multi-environment trials (METs) involving sites across Kebbi, Sokoto, Zamfara, and Katsina States would be a critical next step in confirming their broad-based adaptation and in characterizing genotype × environment interaction patterns (Yan and Kang, 2003; Badu-Apraku and Fakorede, 2014).

Implications for Maize Production in the Sudan Savanna of Northwestern Nigeria

The findings of this study carry significant implications for the organized maize seed sector, agricultural development programs, and smallholder farmer communities in Northwestern Nigeria. The persistent food insecurity in the region, exacerbated by the increasing frequency and severity of dry spells attributable to climate change (IPCC, 2022; Hulme et al., 2001), makes the development of locally adapted, drought-tolerant hybrid varieties not merely an academic exercise but an urgent food security imperative. The three identified elite crosses (L2 × L4, L1 × L2, L1 × L4), if advanced through standard variety development pipelines and subjected to participatory variety selection (PVS) with local farming communities, could realistically be positioned for release within three to four breeding cycles which is a timeline consistent with national variety release procedures under NASC guidelines (NASC, 2020).

Furthermore, the demonstrated utility of L2 (TZEI 23) and L4 (TZEI 41) as superior combining parents has implications for the design of future diallel or factorial crossing programs, which could use these lines as 'tester' parents in top cross screening of larger breeding populations, thereby maximizing efficiency in the identification of superior hybrids for the region. Integration of molecular markers for drought-tolerance QTL (e.g., on chromosomes 1, 6, and 8 as identified by Ribaut et al., 1997; Tuberosa and Salvi, 2006) into marker-assisted selection protocols could further accelerate the development of drought-tolerant varieties by enabling the pyramiding of favorable alleles across the identified elite parents.

CONCLUSION

This study evaluated six tropical maize inbred lines and their 15 F_1 crosses derived from a complete diallel mating design for drought tolerance under managed drought-stressed and well-watered conditions in Zuru, Kebbi State, Nigeria. The following major conclusions are drawn:

i) GCA and SCA effects were highly significant for all traits under both moisture regimes, indicating the importance of both additive and non-additive gene action in the genetic control of drought tolerance traits. The GCA:SCA variance ratio exceeded unity for flowering traits (DTS, DTA, ASI) and plant height, confirming the predominance of additive gene action for these traits and their amenability to conventional selection strategies.

ii) Parental lines L2 (TZEI 23) and L4 (TZEI 41) exhibited the highest and most consistent positive GCA effects for grain yield and negative GCA effects for ASI under drought stress, establishing them as the most valuable parents for drought-tolerant hybrid development in this agroecological zone.

iii) The cross L2 × L4 emerged as the superior hybrid combination with the highest grain yield under drought stress (3.47 t ha^{-1}), shortest ASI (2.4 days), and highest stress tolerance indices (STI = 0.842), making it a strong candidate for advancement to multi-location and on-farm trials. The crosses L1 × L2 and L1 × L4 ranked second and third, respectively, and are also recommended for further evaluation.

iv) Grain yield under drought was significantly and negatively correlated with ASI ($r = -0.84$), confirming the continued validity of ASI as a primary selection criterion for drought tolerance in maize breeding programs targeting the Nigerian Sudan Savanna.

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REFERENCES

1. Ado, S. G., Usman, I. S., Abdulmalik, R. O., Aliyu, U., Maafi, Z., & Luka, L. (2012). Combining ability analysis for yield and its components among open-pollinated maize varieties in the Nigerian Guinea Savanna. Nigerian Journal of Genetics, 26(1), 57–64.
2. Adetimirin, V. O., Kim, S. K., Godwin, I. D., & Menkir, A. (2008). Estimates of combining ability for grain yield and yield components in maize. African Journal of Biotechnology, 7(5), 565–569.
3. Adnan, A. A., Jibrin, J. M., Kamara, A. Y., Abdullahi, I. I., Garba, I. I., & Shaibu, A. S. (2020). CERES-Maize model for simulating the effects of planting date and nitrogen rates on maize growth and yield in northern Nigeria. Frontiers in Plant Science, 11, 477. https://doi.org/10.3389/fpls.2020.00477
4. Akinwale, M. G., Badu-Apraku, B., Fakorede, M. A. B., & Vroh-Bi, I. (2014). Heterotic grouping of IITA early-maturing maize inbred lines based on combining ability in Striga-infested and Striga-free environments and the use of SSR markers. Field Crops Research, 156, 48–62.
5. Aksel, R., & Johnson, L. P. V. (1961). A graphical method for estimating and testing diallel cross. Hereditas, 47, 656–659.
6. ADP Kebbi. (2022). Kebbi State agricultural input recommendations manual (3rd ed.). Kebbi State Agricultural Development Program.
7. Badu-Apraku, B., & Fakorede, M. A. B. (2014). Advances in varietal improvement of early and extra-early maize in sub-Saharan Africa (pp. 1–397). IITA.
8. Badu-Apraku, B., Fakorede, M. A. B., Menkir, A., & Kamara, A. Y. (2010). Levels of tolerance to drought stress of early extra-early maize composites at the seedling stage. Journal of Agronomy, 9(2), 74–80.
9. Badu-Apraku, B., Fakorede, M. A. B., Oyekunle, M., & Akinwale, R. O. (2011). Selection of extra-early maize inbreds under drought and low N environments for hybrid production. Maydica, 56(4), 29–41.
10. Badu-Apraku, B., Fontem Lum, A., Fakorede, M. A. B., Feldman, A., Khan, M. A., Diallo, A., & Coulibaly, M. (2012a). Performance of early-maturing maize cultivars derived from the establishment of a drought-tolerance breeding program in West Africa. Crop Science, 52(5), 2116–2128.
11. Badu-Apraku, B., Oyekunle, M., Akinwale, R. O., & Fontem Lum, A. (2012b). Combining ability of CIMMYT and IITA early-maturing yellow maize inbreds under drought stress and well-watered environments in West Africa. Crop Science, 52(2), 3156–3166.
12. Badu-Apraku, B., Akinwale, R. O., & Menkir, A. (2013). Relationship between stress tolerance traits of inbred lines and derived hybrids of maize under drought, low soil nitrogen, and Striga infestation. Crop Science, 53(3), 1–14.
13. Baker, R. J. (1978). Issues in diallel analysis. Crop Science, 18(4), 533–536.
14. Betrán, F. J., Beck, D., Bänziger, M., & Edmeades, G. O. (2003). Genetic analysis of inbred and hybrid grain yield under stress and nonstress environments in tropical maize. Crop Science, 43(3), 807–817.
15. Beyene, Y., Semagn, K., Mugo, S., Tarekegne, A., Babu, R., Meisel, B., Sehabiague, P., Makumbi, D., Magorokosho, C., Oikeh, S., Gakunga, J., Vargas, M., Olsen, M., Prasanna, B. M., Bänziger, M., & Crossa, J. (2011). Genetic gains in grain yield through genomic selection in eight bi-parental maize populations under drought stress. Crop Science, 55(1), 154–163.
16. Bolanos, J., & Edmeades, G. O. (1993). Eight cycles of selection for drought tolerance in lowland tropical maize. I. Responses in grain yield, biomass, and radiation utilization. Field Crops Research, 31(3–4), 233–252.
17. Bouslama, M., & Schapaugh, W. T. (1984). Stress tolerance in soybean. Part 1: Evaluation of three screening techniques for heat and drought tolerance. Crop Science, 24(5), 933–937.
18. Cairns, J. E., Crossa, J., Zaidi, P. H., Grudloyma, P., Sanchez, C., Araus, J. L., Thaitad, S., Makumbi, D., Magorokosho, C., Banziger, M., Menkir, A., Hearne, S., & Prasanna, B. M. (2012). Identification of drought, heat, and combined drought and heat tolerant donors in maize. Crop Science, 52(3), 1058–1073.
19. CIMMYT. (2000). Laboratory protocols: CIMMYT applied molecular genetics laboratory (3rd ed.). CIMMYT.
20. Crow, J. F. (1948). Alternative hypotheses of hybrid vigour. Genetics, 33(5), 477–487.
21. Dao, A., Sanou, J., Gracen, V., & Danquah, E. Y. (2021). Identifying drought-tolerant maize inbred lines for hybrid production in Burkina Faso. African Crop Science Journal, 29(1), 89–107.
22. Edmeades, G. O., Bolanos, J., Chapman, S. C., Lafitte, H. R., & Bänziger, M. (1999). Selection improves drought tolerance in tropical maize populations: I. Gains in biomass, grain yield, and harvest index. Crop Science, 39(5), 1306–1315.
23. Enyew, M., Tesfaye, K., Endresen, D., Diro, S., Getnet, Z., Afework, Y., & Negash, K. (2021). Genetic diversity, heritability, and traits association of maize (Zea mays L.) genotypes for drought tolerance in Ethiopia. Crop Breeding and Applied Biotechnology, 21(2), e36812132.
24. Falconer, D. S., & Mackay, T. F. C. (1996). Introduction to quantitative genetics (4th ed., pp. 1–464). Longman Group Ltd.
25. FAO. (2024). World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps (World Soil Resources Reports No. 106). Food and Agriculture Organization.
26. FAO. (2023). Crop prospects and food situation—Quarterly global report No. 4. Food and Agriculture Organization of the United Nations.

27. FAOSTAT. (2023). FAOSTAT agriculture database. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/
28. Fasahat, P., Rajabi, A., Rad, J. M., & Derera, J. (2016). Principles and utilization of combining ability in plant breeding. Biometrics and Biostatistics International Journal, 4(1), 1–22.
29. Fernandez, G. C. J. (1992). Effective selection criteria for assessing plant stress tolerance. In C. G. Kuo (Ed.), Adaptation of food crops to temperature and water stress (pp. 257–270). Asian Vegetable Research Development Center.
30. Fischer, R. A., & Maurer, R. (1978). Drought resistance in spring wheat cultivars. I. Grain yield responses. Australian Journal of Agricultural Research, 29(5), 897–912.
31. Fischer, K. S., Johnson, E. C., & Edmeades, G. O. (1983). Breeding and selection for drought resistance in tropical maize. CIMMYT.
32. Gavuzzi, P., Rizza, F., Palumbo, M., Campanile, R. G., Ricciardi, G. L., & Borghi, B. (1997). Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. Canadian Journal of Plant Science, 77(4), 523–531.
33. Golabadi, M., Arzani, A., & Maibody, S. A. M. (2006). Assessment of drought tolerance in segregating populations in durum wheat. African Journal of Agricultural Research, 1(5), 162–171.
34. Griffing, B. (1956). Concept of general and specific combining ability in relation to diallel crossing systems. Australian Journal of Biological Sciences, 9(4), 463–493.
35. Hallauer, A. R., Carena, M. J., & Miranda Filho, J. B. (2010). Quantitative genetics in maize breeding (3rd ed., pp. 1–680). Springer.
36. Hayman, B. I. (1954). The theory and analysis of diallel crosses. Genetics, 39(6), 789–809.
37. Heisey, P. W., & Edmeades, G. O. (1999). Maize production in drought-stressed environments: Technical options and research resource allocation. In CIMMYT 1997/98 world maize facts and trends (pp. 1–36). CIMMYT.
38. Hulme, M., Doherty, R., Ngara, T., New, M., & Lister, D. (2001). African climate change: 1900–2100. Climate Research, 17(2), 145–168.
39. IBM Corp. (2021). IBM SPSS Statistics for Windows (Version 28.0). IBM Corp.
40. IITA. (2012). Maize improvement for the developing world. IITA.
41. IPCC. (2022). Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
42. Lafitte, H. R., Edmeades, G. O., & Taba, S. (2003). Adaptive strategies identified among tropical maize landraces for drought tolerance. Field Crops Research, 39(3), 1–9.
43. Mather, K., & Jinks, J. L. (1982). Biometrical genetics: The study of continuous variation (3rd ed., pp. 1–396). Chapman and Hall.
44. Menkir, A. (2006). Genetic variation for agronomic and biochemical traits in IITA-bred maize inbred lines. Journal of Genetics and Genomics, 33(7), 637–651.
45. Menkir, A., & Akintunde, A. O. (2001). Evaluation of the performance of maize (Zea mays L.) germplasm accessions under drought-stress conditions. Maydica, 46(1), 23–33.
46. Meseka, S., Menkir, A., Ibrahim, A. E. S., & Ajala, S. O. (2006). Genetic analysis of performance of maize inbred lines selected for tolerance to drought under low nitrogen. Maydica, 51(3–4), 487–495.
47. Meseka, S. K., Menkir, A., Fakorede, M. A. B., Ajala, S. O., & Badu-Apraku, B. (2013). Introgression of genes for tolerance to drought and low nitrogen into adapted maize cultivars in West Africa. Journal of Crop Improvement, 27(2), 123–144.
48. Mitra, J. (2001). Genetics and genetic improvement of drought resistance in crop plants. Current Science, 80(6), 758–763.
49. NASC. (2020). National Agricultural Seeds Council variety registration procedures and guidelines. National Agricultural Seeds Council.
50. Pingali, P. L. (2001). CIMMYT 1999–2000 world maize facts and trends: Meeting world maize needs: Technological opportunities and priorities for the public sector. CIMMYT.
51. R Core Team. (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/
52. Ribaut, J. M., Jiang, C., González-de-León, D., Edmeades, G. O., & Hoisington, D. A. (1997). Identification of quantitative trait loci under drought conditions in tropical maize. 2. Yield components and marker-assisted selection strategies. Theoretical and Applied Genetics, 94(6), 887–896.
53. Rosielle, A. A., & Hamblin, J. (1981). Theoretical aspects of selection for yield in stress and non-stress environments. Crop Science, 21(6), 943–946.
54. SAS Institute. (2014). SAS/STAT user's guide (Version 9.4). SAS Institute Inc.
55. Semagn, K., Magorokosho, C., Ogugo, V., & Sida, A. (2015). Quantitative trait loci mapping and molecular breeding for developing stress tolerant maize for Sub-Saharan Africa. African Journal of Biotechnology, 14(7), 560–573.

56. Shiferaw, B., Prasanna, B. M., Hellin, J., & Banziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. Food Security, 3(3), 307–327.
57. Shull, G. H. (1908). The composition of a field of maize. Journal of Heredity, 4(1), 296–301.
58. Sprague, G. F., & Tatum, L. A. (1942). General vs specific combining ability in single crosses of corn. Journal of the American Society of Agronomy, 34(10), 923–932.
59. Temesgen, T., Mwangi, M., Mwangi, W., & Beyene, Y. (2015). Combining ability analysis and performance evaluation of single cross maize hybrids under drought stress condition. SpringerPlus, 4, 646.
60. Tollenaar, M., & Wu, J. (1999). Yield improvement in temperate maize is attributable to greater stress tolerance. Crop Science, 39(6), 1597–1604.
61. Tuberosa, R., & Salvi, S. (2006). Genomics-based approaches to improve drought tolerance of crops. Trends in Plant Science, 11(8), 405–412.
62. USDA. (2024). Nigeria grain and feed annual 2024. USDA Foreign Agricultural Service, GAIN Report.
63. Vasal, S. K., Srinivasan, G., Pandey, S., Gonzalez, C. F., & Beck, D. L. (1992). Heterosis and combining ability of CIMMYT's tropical × subtropical maize germplasm. Crop Science, 32(4), 884–890.
64. Yadav, V. K., Singh, I. S., & Dhaka, S. R. (2006). Combining ability analysis for yield and yield contributing characters in bread wheat (Triticum aestivum L.). Research on Crops, 7(3), 657–661.
65. Yan, W., & Kang, M. S. (2003). GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists (pp. 1–271). CRC Press.
66. Zhang, Y., Kang, M. S., & Lamkey, K. R. (2005). DIALLEL-SAS05: A comprehensive program for Griffing's and Gardner-Eberhart analyses. Agronomy Journal, 97(4), 1097–1106.
67. Ziyomo, C., & Bernardo, R. (2013). Drought tolerance in maize: Indirect selection through secondary traits versus genomewide selection. Crop Science, 53(4), 1269–1275.

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