MadrasAgric.J.,2024; https://doi.org/10.29321/MAJ.10.0MMA27

RESEARCH ARTICLE

Identification of Drought-Tolerant Maize Inbred Lines Through Morphophysiological Traits

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Received: 27 Apr 2024

Revised: 29 May 2024

Accepted: 12 Jun 2024

ABSTRACT

Drought stress is a critical constraint to maize productivity, particularly in tropical regions where irrigation resources are limited. To identify drought-tolerant maize genotypes and establish physiological benchmarks for future breeding, a total of 90 diverse inbred lines were screened under managed drought conditions during the Rabi-Summer 2019 season at Tamil Nadu Agricultural University, Coimbatore. Drought stress was imposed from the pre-flowering to flowering stages. Significant genotypic variation was observed for key morpho-physiological traits, including anthesis-silking interval (ASI), chlorophyll content, relative water content (RWC), photosynthetic rate, and transpiration rate. Genotypes such as CBM-DL-448, CBM-DL-435, and CBM-DL-238 displayed high grain yield, efficient photosynthesis, and better canopy temperature regulation under stress. Further evaluation of 14 top-performing lines under well-watered conditions revealed no yield penalty, indicating stable performance across environments. The study highlights the utility of integrating secondary traits such as ASI, SPAD, and CTD with yield for screening drought tolerance. It provides a foundation for selecting parental lines for drought-resilient breeding programs. The findings also offer a physiological dataset that can aid in future efforts on marker-assisted selection and developing drought-resilient maize hybrids.

Keywords: Drought tolerance, Stress tolerance, Abiotic stress, Maize

INTRODUCTION

Maize is a multipurpose crop with a global share of 12–13% of its production used for human consumption, with the rest being utilized for several other purposes. Fifteen million farmers in India are engaged in maize cultivation. Only 15% of the cultivated area of maize is under irrigation, and water limitation continues to be a major challenge for the sustainability of maize production. Nutrient and water availability remain the two most restrictive resources in crop production (Boyer, 1982; Lea and Azevedo, 2006; Moser et al., 2006). Drought affects maize throughout its growth cycle, with germination and early developmental stages being particularly sensitive (Edmeades et al., 1999; Zenda et al., 2020).

Turner (1996) indicated that for plants to survive water imbalances, they must possess a range of both morphological and biochemical mechanisms that enable growth and reproduction under water-limited conditions. Adaptation to climate change may involve

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the use of crop varieties that are tolerant to higher temperatures and drought, and resistant to emerging pests and diseases (Fahad et al., 2017). Unless strong adaptation measures are implemented, especially against heat and drought stresses, yield losses of 10% to 20% in maize and other staple crops are projected, potentially leading to a marked decline in human welfare.

Approaches that enhance the performance of maize genotypes under combined drought and heat stress (DSHTS) are, therefore, essential to sustaining productivity. Breeding for drought tolerance remains the most practical approach to mitigating the impact of drought stress (Messmer et al., 2009; Bolaños et al., 2021). Identifying base populations suitable for breeding is the first critical step (Flint-Garcia et al., 2005), and the identification of adaptive traits associated with drought tolerance is vital for designing effective breeding strategies.

Significant research has been undertaken to unravel the genetic and molecular mechanisms underlying drought tolerance in maize, with the aim of integrating this knowledge into traditional breeding programs through molecular markers, genomic selection, and advanced phenotyping (Gupta et al., 2020; Adebayo et al., 2023). In view of these ongoing challenges and scientific advancements, the present study was undertaken with the following objective: (1)to screen maize inbred lines for drought tolerance based on physiological traits,(2) identify drought-tolerant maize inbred lines with potential for use as parental lines in future breeding programs and, (3)generate baseline data on physiological and morphological responses of maize inbred lines under drought stress for use in marker-assisted selection and other breeding strategies.

MATERIALS AND METHODS

The experiment was carried out at Block 36E of Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India (11.0136 °N, 76.9378 °E; 436.8 m a.s.l.) during Rabi-Summer 2019. The field consisted of sandy clay loam soil with a pH of 8.17, electrical conductivity (EC) of 1.25 dS/m, and a field capacity of 30.65%. A total of 90 diverse maize inbred lines sourced from the Indian Agricultural Research Institute, New Delhi, were evaluated using an Augmented Block Design. Each block included two control (inbred checks: UMI 1200 and UMI 1230). Each plot measured 3.5 m in length and was sown with 15 seeds at a spacing of 60 cm × 25 cm.Weather data during the crop growth period are presented in Figure 1. Although rainfall occurred during April and May, it was insufficient to mitigate drought stress under elevated temperatures. Maximum daytime and night-time temperatures reached 38.5 °C and 27 °C, respectively, which adversely affected fertilization, seed set, and grain filling. Optimal temperatures for maize growth in tropical lowlands are approximately 27 °C (day) and 20 °C (night). Drought stress was therefore imposed during the late vegetative and reproductive stages. The data were recorded on

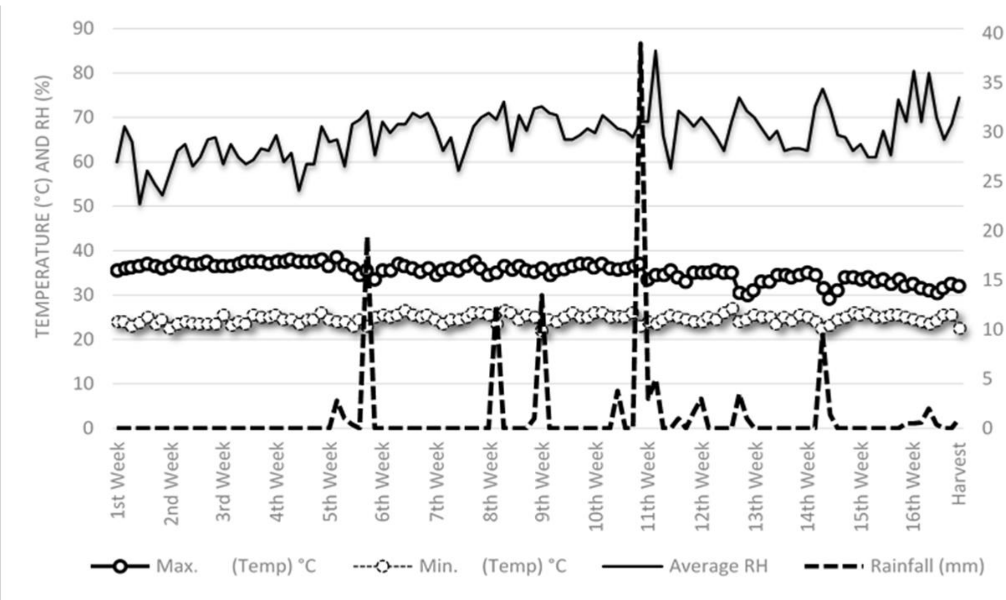

Figure 1. Weather data prevailing during the experimental period

physiological and morphological traits as follows. The top performing inbred lines under drought stress were further evaluated under irrigated condition.

Physiological Traits

- *Chlorophyll Index* was measured using a SPAD meter (SPAD 502, Minolta Co., Tokyo) at 65 days after sowing (DAS) between 09:00 and 12:00 hrs. SPAD values were recorded from the top, middle, and bottom sections of the topmost fully matured leaf on three randomly selected plants per plot.
- *Canopy Temperature and Canopy Temperature Depression (CTD)* were recorded at 68 DAS using a FLUKE VT04 Visual IR Thermometer on three central plants per plot. CTD was calculated as

$$CTD = Ta - Tc,$$

Where Ta is the ambient temperature and Tc is the canopy temperature.

- *Leaf Rolling* was observed at 66 DAS when soil moisture dropped below 20%, with recordings taken during 10:00–12:00 hrs and 15:30–17:00 hrs using the CIMMYT (2000) scale:
  1 = turgid leaves;
  3 = V-shaped rolling;
  5 = onion-type rolling.
- *Chlorophyll Content and Relative Water Content (RWC):*SPAD readings were taken at 65 DAS from the leaf above the cob (10 plants per replication). Chlorophyll Stability Index was determined according to Murphy (1962). Relative water content was calculated following Turner (1981).
- *Leaf Area and Leaf Area Index (LAI):* At anthesis (60 DAS), leaves from three randomly selected plants per plot were measured using a leaf area meter. LAI was computed using plant spacing (60 cm × 20 cm = 1200 cm² per plant).
- *Gas Exchange Parameters:* Photosynthetic rate, stomatal conductance, and transpiration rate were recorded at 65 DAS using the LI-6400XT Portable Photosynthesis System on the leaf above the cob under steady light and CO_2 conditions.

Biometrical Traits

Five central plants were randomly selected from each plot and evaluated for the following traits: days to tasseling and silking, plant height, leaf length and breadth, number of tassel branches, tassel length, cob placement height, cob length, number of kernels per row, number of rows per cob, 100-kernel weight, and single plant yield.

Data Analysis

Data analysis was performed using the IBM SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Evaluation of inbred lines under drought stress condition

Drought remains one of the most devastating abiotic stresses limiting maize productivity worldwide, with combined drought and heat stress potentially causing yield losses exceeding 40% (Lobellet al., 2011). The development of drought-tolerant maize genotypes is thus a critical strategy to mitigate the adverse impacts of climate change and ensure food security. The present study was undertaken to assess genetic variability in a large set of maize inbred lines and to identify promising lines for further breeding efforts based on their physiological and yield-related responses to drought stress. The total of 90 genotypes were assessed for flowering and secondary traits such as grain yield, chlorophyll content, leaf rolling, and anthesis-silking interval (ASI), which are well-established indicators of drought tolerance. The genotypes exhibited marked variation in their responses, particularly in flowering behaviour under the imposed water stress. Analysis of variance (Tables 1 and 2) revealed significant differences among the inbred lines for most of the measured yield-related and physiological traits, indicating genetic variability. All traits showed statistically significant variation ($p < 0.05$) except for leaf rolling, which did not vary significantly across genotypes.

The observations of morpho-physiological traits are presented in Table 3. The plant height has been ranged from 58.3 cm to 167 cm with the average of 105.68 cm. The average ear placement heights were 56.29 cm and ranges between 36 cm and 77.1 cm. Anthesis-silking interval (ASI) was another critical trait reflecting drought resilience. ASI, in particular, has been widely recognized as a reliable proxy for reproductive success under water stress (Bänziger et al., 2000; Edmeades et al., 1993), and shorter ASI is strongly associated with enhanced synchrony between male and female flowering, resulting in improved seed set and grain yield. Several genotypes, including CBM-DL-95, 448, 549, 535, 322,

Table1. ANOVA for different morphophysiological traits in the preliminary phenotyping experiment.

Source	LL	LB	TL	TB	EH	CL	SW	GW
Block	78.2278*	0.4216*	12.928*	5.6338	89.6942*	3.7276	8.7249	14.6116
TREAT	147.329**	1.7674**	36.1416**	15.4016**	103.354**	9.2476**	12.3805**	1084.9637**
CHECKS	979.0133**	10.1475**	204.9645**	158.0467**	379.5492**	115.2795**	60.1897**	14074.6189**
T. ENTRY	131.0962**	1.4706**	30.4698**	9.0107	111.142**	4.5696	8.8132	106.7955**
CHKvTEST	-1734.6905	-5.3415	-134.3626	13.6081	-1694.5593	1.4655	138.6336**	36183.3194**
ERROR	13.7633	0.1507	6.2285	6.0467	16.7092	4.4525	6.462	21.448

Table 2. ANOVA for different morphophysiological traits in the preliminary phenotyping experiment.

Source	LL	LB	TL	TB	EH	CL	SW	GW
Block	78.2278*	0.4216*	12.928*	5.6338	89.6942*	3.7276	8.7249	14.6116
TREAT	147.329**	1.7674**	36.1416**	15.4016**	103.354**	9.2476**	12.3805**	1084.9637**
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36, and 110, exhibited no ASI delay, indicating good synchronization between male and female flowering. A one-day ASI delay, which is generally acceptable under stress, was observed in genotypes such as CBM-DL-169, 165, 38, 152, 216, 238, 360, 200, and 80. In contrast, prolonged ASI exceeding seven days was recorded in several lines, including CBM-DL-264, 491, 225, 382, 353, 498, 488, 273, 442, 415, 201, 451, and 291, suggesting poor floral synchrony under stress. Our results are in agreement with earlier findings by Ziyomo and Bernardo (2013). The average grain weight across all genotypes was 27.92 g. Based on grain weight, high-yielding genotypes included CBM-DL-448 (57.4 g), CBM-DL-435 (51.7 g), CBM-DL-238 (50.2 g), CBM-DL-322 (49.3 g), CBM-DL-200 (46.2 g), and CBM-DL-289 (46.0 g). Moderately high yields were recorded in genotypes such as CBM-DL-111, CBM-DL-157, CBM-DL-164, CBM-DL-80, CBM-DL-38, CBM-DL-360, and CBM-DL-333, with grain weights ranging from approximately 41 to 45 g. Cob length also varied considerably, with the longest cobs observed in CBM-DL-358 (16.4 cm) and CBM-DL-113 (15.0 cm), while CBM-DL-95 and CBM-DL-378 recorded the shortest cobs. .

Leaf rolling scores under drought stress further differentiated the genotypes. Some lines, including CBM-DL-533, 358, 363, 75, 373, 529, 435, 558, 451, 356, 38, and 80, maintained turgid leaves with a score of zero, indicating better water retention and drought tolerance. On the other hand, lines such as CBM-DL-17, 275, 157, 378, 377, 376, 398, 42, 498, 291, 448, 535, and 503 showed fully rolled leaves, potentially compromising photosynthetic activity.The mean chlorophyll content across the inbred lines was 30.81 SPAD units. Several genotypes maintained significantly higher chlorophyll levels under stress, including CBM-DL-165 (43.52 SPAD), CBM-DL-313 (39.48), CBM-DL-13 (39.22), CBM-DL-360 (39.25), CBM-DL-354 (38.99), and CBM-DL-322 (38.22). Other lines with comparatively high SPAD values included CBM-DL-38, 491, 548, 95, 164, 23, 382, 113, 307, 142, 84, 110, and 80, suggesting that these genotypes may have sustained higher photosynthetic activity during drought stress. The genotypes maintains unrolled or less-rolled leaves under water deficit, suggesting efficient water use strategies and osmotic adjustment. Similar responses have been linked to sustained stomatal conductance and photosynthesis under drought (Campos et al., 2004; Trachsel et al., 2011). Overall, the inbreds such as CBM-DL-448, CBM-DL-435, and CBM-DL-238, exhibited high grain yield, shorter ASI, and high chlorophyll retention under drought stress. These genotypes will serves as the potential candidate for drought tolerance breeding in maize and can be used as the parents in the drought tolerant hybrid development.

Evaluation of Selected Inbred Lines under Irrigated Conditions

To address concerns regarding potential yield penalties under non-stress conditions, a phenomenon commonly observed in drought-bred materials (Edmeades et al., 1993). The top 14 lines performing well under drought stress conditions were evaluated further under well-watered conditions. Analysis of variance (Table 4) indicated significant differences among genotypes for all measured traits, confirming the presence of genetic variability. The mean values of the morpho-physiological traits for each genotype are presented in Table 5. In terms of photosynthetic efficiency, the highest photosynthetic rates were recorded in CBM-DL-238 (41.82 µmol CO_2 m^{-2} s^{-1}), CBM-DL-360 (41.67 µmol CO_2 m^{-2} s^{-1}), and CBM-DL-435 (41.34 µmol CO_2 m^{-2} s^{-1}), indicating superior carbon assimilation potential under optimal moisture conditions. In contrast, the lowest rate was observed in the check line UMI 1200, which recorded a photosynthetic rate of 27.71 µmol CO_2 m^{-2} s^{-1}. When assessing transpiration rates (TR) under drought stress, CBM-DL-289-1 (1.065 mmol H_2O m^{-2} s^{-1}), CBM-DL-333-1, and CBM-DL-435-1 (both 1.00 mmol H_2O m^{-2} s^{-1}) exhibited the highest rates, suggesting active gas exchange under limited water availability. In contrast, the lowest TR values were recorded in CBM-DL-200-1 and CBM-DL-38-1 (0.385 mmol H_2O m^{-2} s^{-1}), as well as in the check UMI 1230 (0.395 mmol H_2O m^{-2} s^{-1}), reflecting a more conservative water use strategy. Under irrigated conditions, transpiration rates were notably higher, with CBM-DL-322-1 (2.36 mmol H_2O m^{-2} s^{-1}), CBM-DL-435-1 (2.305 mmol H_2O m^{-2} s^{-1}), and CBM-DL-313-1 (2.27 mmol H_2O m^{-2} s^{-1}) recording the highest values, indicating increased stomatal conductance and potential for higher photosynthetic productivity.

With respect to yield parameters, all evaluated inbred lines outperformed the adapted check varieties UMI 1200 and UMI 1230. The highest single plant grain yields were obtained in CBM-DL-448 (196.4 g) and CBM-DL-164 (196.1 g), highlighting their strong yield potential under irrigated conditions.

MadrasAgric.J.,2024;https://doi.org/10.29321/MAJ.10.0MMA27

Table 3.Morphophysiological traits means of inbred lines in the preliminary phenotyping experiment.

Inbred number	CC	CTD	LR	DT	DS	ASI	PH	LL	LB	TL	NTB	EH	CL	100KW	GW
CBM-DL-157	22.870	-0.48**	4	59	63	4	119.1	73*	7.3	28.2	9	61.5	9.6	27.64	44.56*
CBM-DL- 169	36.69**	2.520	1	59	60**	1*	94.8**	77**	7	35.2*	5	68.9*	9.9	26.45	25.25
CBM-DL -165	43.52**	1.440	1	54**	55**	1*	124.8**	71	8.2*	37.1**	5	62.4	12.2	29.24	42.84*
CBM-DL- 333	31.770	1.940	1	53**	55**	2	135.2*	73*	6.4	21.2	3	68*	9.4	32.12	40.97*
CBM-DL 548	36.35**	1.580	1	55**	59**	4	167**	71	7.1	31.6	4	55.9	11.2	24.97	35.08
CBM-DL 217	32.660	1.520	3	65	67	2	103.1	68.5	9.2**	34.1	7	57.3	12.5	32.04	33.18
CBM-DL-13	39.22**	1.480	1	56**	59**	3	125.40	82**	6.4	32.8	6	59.6	13.1	26.04	28.22
CBM-DL -75	32.730	1.90	0	63	67	4	58.30	69.5	6.5	20.6	14	56.4	12.8	27.6	23.17
CBM-DL-264	27.660	0.780	2	67	75	8	103.50	54	8.5**	33.3	6	60.1	11.2	29.74	17.26
CBM-DL -95	35.19**	3.340	3	64	64	0**	840	72.5*	6.6	25.2	7	44.8	5.5	26.3	14.9
CBM-DL -373	29.730	1.50	0	58	62*	4	1120	61	5.9	22.3	5	49.4	11	31.8	40
CBM-DL -405	26.350	3.020	3	63	69	6	97.3**	33	7	28.6	13	46.7	11.1	26.5	36.4
CBM-DL -17	24.470	2.440	4	60	62*	2	107.1**	35	5	25.2	4	36	11.2	29.1	25
CBM-DL -367	34.22*	3.940	2	59	62*	3	83.3**	44	6.3	310	7	49.4	11.3	33.4	22.4
CBM-DL-21	29.450	2.360	1	63	65	2	119.5**	67	8*	24.4	5	64.7	9.1	23.7	17.8
CBM-DL -377	33.240	1.940	4	68	74	6	85.3**	52	6.2	19.7	7	43.9	8.3	27.3	16.5
CBM-DL -376	28.020	1.440	4	61	67	6	95.4**	80.5**	7.2	24.5	14	60.6	9.5	22.3	16.4
CBM-DL -139	17.770	-2.12**	3	58	64	6	97.8**	35	5.5	26.9	7	49	8.6	24.5	21.8
CBM-DL -38	37.74**	1.980	0	55**	56**	1*	135.4**	52.5	4.6	28.7	4	71.7	8.2	27.6	41.9*
CBM-DL -503	32.640	0.3*	5	61	68	7	110.2**	76**	8*	34.1	11	58.7	14	26.7	29.9
CBM-DL -262	26.410	3.880	2	58	60**	2	119.1**	79**	8.5**	29.9	8	59.6	11.2	31.1	26.1
CBM-DL -275	23.590	-1.6**	4	58	60**	2	112**	57	6.6	26.1	6	58.7	12.4	28.8	25.3
CBM-DL -491	36.64**	-1.46**	3	58	66	8	121.7**	65.5	6	24.8	10	67.1	10.7	27.9	24.3
CBM-DL -152	28.630	3.780	3	66	67	1*	104.9**	58	5.2	27.3	5	61.5	12.4	30.8	38.8
CBM-DL -527	24.740	1.480	2	56**	60**	4	129.7**	63	9**	290	14	56.9	12.4	32.9	37.3
CBM-DL -63	34.14*	-2.2**	3	60	64	4	114.6**	69	7	28.2	18	69.8	10.3	26.7	27.5
CBM-DL -159	30.470	-0.58**	3	56**	59**	3	126.2**	61	6	28.2	7	79.1	6.2	26.8	17

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Inbred number	CC	CTD	LR	DT	DS	ASI	PH	LL	LB	TL	NTB	EH	CL	100KW	GW
CBM-DL -442	27.920	2.420	3	64	73	9	140.1**	74*	8.3**	24.2	6	60.6	10.7	25.1	17.3
CBM-DL -354	38.99**	2.10	0	57**	60**	3	104.9**	62	5	16.3	3	73.5	10.3	29	25.3
CBM-DL -216	32.730	3.820	1	55**	56**	1*	155.7**	71	4.8	25.3	4	73.4	9.1	25.2	19.8
CBM-DL -120	34.05*	2.380	1	57**	60**	3	120.8**	47.5	4.9	26.1	7	60.6	10.3	28.5	17.8
CBM-DL -23	35.68**	1.080	1	61	67	6	128.2**	49	7	18.9	5	69.4*	12.4	25.7	30.5
CBM-DL -42	23.640	3.130	4	59	66	7	100**	72.5*	5	34.9*	5	63	9.9	29.5	26.3
CBM-DL -289	28.820	0.920	3	58	60**	2	95.5**	59.4	7.6	270	8	50.6	10.1	30.5	46**
CBM-DL -313	39.48**	0.06**	2	58	62*	4	106.3**	67.8	9.2**	30.5	14	71.5**	9.8	30.3	41.8*
CBM-DL -265	32.760	1.70	1	58	60**	2	136.6**	57	7.4	43**	4	75.7**	12.7	25	33.7
CBM-DL -372	32.790	0.980	3	57**	60**	3	102.5**	71.6*	6.6	38**	7	42.5	11.6	28.8	33.7
CBM-DL 225	33.43*	2.140	3	57**	65	8	97.7**	63.4	6.5	30.2	4	42.6	13	26.7	33.3
CBM-DL -398	24.850	0.1**	4	56**	62*	6	86.5**	74.4*	7.2	27.3	10	77.1**	13.6	29.1	32.9
CBM-DL -316	27.170	4.020	3	66	73	7	97.1**	55	6.1	24.1	6	52.4	11.2	29	28.3
CBM-DL -533	31.380	3.520	0	54**	57**	3	140.1**	42.2	4.8	35.8*	9	46.6	14	27.8	24.9
CBM-DL -448	21.770	3.560	4	67	67	0**	77.8**	61.5	7.4	30.3	14	54	8	26.1	57.4**
CBM-DL -238	25.440	1.980	3	57**	58**	1*	114.6**	55.9	7.2	33.6	5	57.4	12.8	25.3	50.2**
CBM-DL -358	26.240	3.680	0	58	61**	3	113.1**	68.4	7.3	30.5	8	57.8	16.4	30.3	31.9
CBM-DL -382	36.49**	4.180	2	60	68	8	112.9**	64	7.8	32.8	9	59.6	12.2	26.7	28.7
CBM-DL -113	35.01**	0.38*	2	63	63	0**	134.9**	69	7.7	23.1	9	68*	15	27.8	28.3
CBM-DL -203	32.350	1.420	2	58	60**	2	106.3**	55	6.6	30.2	9	60.2	8.7	26.4	22.4
CBM-DL -415	25.260	-3.24**	3	66	75	9	104**	63	8.1*	21.4	12	72.6**	7.7	27	17.6
CBM-DL -451	33.020	1.580	0	68	78	10	73.8**	65	8*	30.7	10	38.3	9.1	28.7	20.9
CBM-DL -164	36.66**	0.860	2	58	64	4	136.8**	71	5	27.3	9	57.8	12.4	30.8	44.5*
CBM-DL -329	28.950	-0.59**	2	59	62*	3	58.3**	76**	5	29.5	5	44.8	9.1	19.8	13.9
CBM-DL -332	24.640	2.320	2	59	62*	3	144.8**	59	8*	180	6	68*	12.8	25.1	21.8
CBM-DL -378	25.420	2.680	4	58	63	5	118.2**	63	5	26.5	9	59.6	5.9	26.6	15.1
CBM-DL -201	25.850	2.910	2	70	79	9	115.5**	81**	8*	240	10	55.9	6.1	29.6	12.3
CBM-DL -151	29.110	4.110	1	67	73	6	89.4**	54	5.5	21.4	5	43.9	10.3	31.7	29.8
CBM-DL -145	28.810	3.860	2	67	74	7	90.7**	51	6.1	27.3	8	30.9	14.6	28.8	27.2

Inbred number	CC	CTD	LR	DT	DS	ASI	PH	LL	LB	TL	NTB	EH	CL	100KW	GW
CBM-DL -83	34.94**	-0.56**	1	58	63	5	114.5**	39	6.2	16.5	15	41.1	7.4	32.8	17.3
CBM-DL -356	32.410	2.760	0	60	60**	0**	110.6**	41	7	29.9	10	50.4	13.7	25.3	28.5
CBM-DL -543	25.480	0.36*	2	65	72	7	74.7**	33	5.3	26.5	8	45.7	10.6	25.2	17.2
CBM-DL -270	28.950	-0.82**	2	69	76	7	92**	37	5.5	29.9	7	36.5	12	23.8	16.8
CBM-DL -529	32.780	2.50	0	58	62*	4	101.7**	53	5.9	270	9	49.4	7.1	25	16
CBM-DL -360	39.25**	3.80	2	68	69	1*	124.5**	64	7.4	8.2	7	64.3	9.3	27.1	41.9*
CBM-DL -549	28.090	-0.78**	1	58	58**	0**	103.5**	48	4.5	19.3	10	61.5	9.8	24.7	22.9
CBM-DL -535	27.050	4.480	4	68	68	0**	102.6**	61	6.8	21.8	11	67.1	11.6	27.8	22
CBM-DL -111	32.520	1.020	3	60	64	4	98.1**	59	6	32.1	12	57.8	8	21.9	45*
CBM-DL -307	36.12**	20	1	59	61**	2	102.2**	64	8*	31.6	10	57.8	11	25.7	21.5
CBM-DL -531	28.310	3.40	3	59	61**	2	75.1**	64	7.4	29.5	9	50.4	10.3	22.9	13.6
CBM-DL -435	33.62*	1.240	0	60	65	5	107.5**	70	7	26.5	10	62.4	7.3	28.6	51.7**
CBM-DL -558	33.47*	0.22*	0	71	76	5	96**	60	6.5	30.7	11	55.9	11.8	23.8	21.9
CBM-DL -142	35.27**	1.520	2	54**	59**	5	90.7**	59	6	37.5**	6	43.9	9.5	30.8	20.6
CBM-DL -331	33.380	1.560	3	66	68	2	88.4**	75**	7.4	34.5*	9	58.7	8.3	24.8	19.8
CBM-DL -353	29.960	4.120	3	68	76	8	69.4**	63	6.6	21.8	10	38.3	9.5	28.6	26.4
CBM-DL -84	35.32**	5.10	1	58	60**	2	123.1**	62	6	28.6	5	55	9.9	29.8	20.1
CBM-DL -291	21.870	0.54*	4	58	68	10	80**	45	5.5	28.2	8	36.5	11	34.5	20.1
CBM-DL -322	38.22**	3.820	2	56**	56**	0**	108.4**	61	6	34.1	6	54.1	10.2	23.7	49.3**
CBM-DL -363	30.160	4.620	0	59	62*	3	110.6**	73*	8.8**	28.6	11	71.7**	9.9	28	14.8
CBM-DL -223	30.820	1.340	1	59	61**	2	76**	54.5	6	25.2	5	55	11.8	24.5	25.5
CBM-DL -36	25.880	20	1	61	61**	0**	118.6**	49	6.3	26.1	7	57.8	14	27.5	24.5
CBM-DL -202	23.090	1.10	2	64	69	5	99.5**	54	7.6	26.5	6	41.1	9.9	21.8	23.8
CBM-DL -506	27.070	2.380	2	60	67	7	88.9**	68	8.4**	27.3	10	51.3	11.2	27.1	34.4
CBM-DL -200	33.49*	1.940	1	58	59**	1*	92.9**	69	4.4	28.6	6	50.4	6.8	25.2	46.2**
CBM-DL -441	32.740	3.340	3	57**	61**	4	72.9**	58	8*	25.2	11	48.5	9.9	27.6	26.7
CBM-DL -260	32.490	2.460	3	56**	59**	3	109.3**	60	6	32.4	8	58.7	10.7	32.2	19.9
CBM-DL -110	35.64**	3.40	2	60	60**	0**	96.9**	56	8.9**	240	6	55.9	10.1	28.1	25.2
CBM-DL -498	30.050	1.460	4	61	69	8	94.2**	60	7.2	23.1	9	63.3	11.2	34.2	23.1

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Inbred number	CC	CTD	LR	DT	DS	ASI	PH	LL	LB	TL	NTB	EH	CL	100KW	GW
CBM-DL -50	30.160	3.960	1	58	64	6	87.6**	57	7.4	31.2	6	45.7	13.3	31.4	36.6
CBM-DL -488	23.240	3.50	2	63	71	8	111.5**	71	8.4**	20.1	10	63.3	12.1	25.7	24.9
CBM-DL -80	35.23**	4.10	0	59	60**	1*	123.5**	76**	8.8**	29.9	9	61.5	9	22.1	42.4*
CBM-DL -314	32.850	0.660	3	61	66	5	92**	58	6.5	19.3	7	49.4	10.3	27.1	21.7
CBM-DL -273	27.580	0.960	3	59	67	8	84.4**	57	6.5	21.4	7	40.2	9.1	28.1	21.1
Test mean	30.8124	1.8631	2.0556	60.3667	64.3889	4.0222	105.6844	61.1344	6.7644	27.4389	8.0222	56.2956	10.5856	27.5782	27.9262
CD (0.05)	2.5977	1.3185	3.0072	2.4311	2.2091	2.6089	13.8109	10.3882	1.0869	6.9883	6.8855	11.4461	5.9085	7.1181	12.968

CC: Chlorophyll content (spad units), CTD- Canopy temperature depression, LR- Leaf Rolling, DT- Days to Tasseling (days) , DS- Days to Silking (days), ASI- Anthesis Silking interval (days), PH- Plant Height (cm), LL- Leaf Length (cm), LB- Leaf Breadth (cm), TL-Tassel Length (cm), NTB- Number of Tassel Branches (cm), EH- Ear Height (cm), CL- Cob Length (cm), 100KW- Hundred kernel height (g), GW- Grain Weight (g).

Table 4. ANOVA for morpho-physiological traits in evaluation of selected drought tolerant inbred lines under irrigated conditions.

Source of variation	df	CC	LA	LAI	RWC	LOV	PR	SC	TR	CL	NKR	NK/R	100KW	SPY
Replications	1	0.551	13.261	0.023	7.703	4.938	3.84	0.01	0.198*	0.32	1.125	9.031	0.828	1.569
Treatments	15	17.869**	3387403.239**	3.921**	67.602**	396.269**	26.5**	0.004**	1.971**	12.879**	9.658**	35.365**	53.761**	2604.848**
Error	15	3.787	25.465	0.027	16.326	4.907	3.759	0.022	0.038	0.063	0.592	4.565	0.978	7.913

* and**Significant at 5 and 1 % level

CC: Chlorophyll content (spad units), LA: Leaf area (cm^2), LAI: Leaf area index, RWC: Relative water content, LOV: Leaf orientation value, PR: Photosynthetic Rate (ɥmol $m^{-2}s^{-1}$), Stomatal conductance (mol H2O $m^{-2}s^{-1}$), TR: Transpiration rate (mmol H2O $m^{-2}s^{-1}$), CL: Cob length (cm), NK/R: Number of kernels per row, NKR: Number of kernel rows, SPY: Single plant yield (gm), 100 KW: 100 Kernel weight (gm).

Table 5. Mean values of various physiological and yield traits of 16 selected maize inbred lines under irrigated conditions.

Genotypes	CC	LA	LAI	RWC	LOV	PR	SC	TR	CL	NKR	NK/R	100KW	SPY
CBM-DL-38	55.05^{ab}	3564.15^{m}	4.075^{h}	74.785^{defgh}	63.988^{a}	33.323^{c}	0.20^{2}f	6.483^{c}	16.45^{g}	12^{de}	31^{cdef}	37.601^{c}	124.315^{f}
CBM-DL-80	51.04^{bcde}	5712.94^{f}	6.445^{d}	78.44^{bcdefg}	54.314^{b}	36.808^{bc}	0.235^{de}	6.939^{b}	16.85^{fg}	14^{bc}	32.5^{bcd}	33.345^{ef}	154.705^{d}
CBM-DL-111	50.14^{cde}	7339.8^{a}	8.065^{a}	89.67^{a}	37.386^{e}	35.46^{8c}	0.273^{bc}	7.737^{a}	17.35^{ef}	15^{b}	27.5^{efgh}	33.958^{de}	103.109^{h}
CBM-DL-157	49.12^{de}	4917.01^{j}	5.359^{fg}	79.005^{bcdefg}	63.22^{a}	36.177^{c}	0.243^{d}	6.681^{bc}	17.6^{e}	14b^{c}	30^{defg}	36.559^{c}	139.38^{e}
CBM-DL-164	53.5a^{bc}	5660.96^{g}	6.425^{d}	71.955^{fgh}	46.65^{c}	34.543^{c}	0.234^{de}	5.824^{de}	20.7^{a}	18^{a}	35.5^{abc}	32.796^{ef}	196.1^{a}
CBM-DL-200	53.82^{abc}	6186.05^{c}	6.74c^{d}	70.805^{gh}	38.603^{e}	34.876^{c}	0.215^{ef}	5.966^{d}	14.1^{i}	13^{cd}	25^{h}	35.623^{cd}	117.725^{g}
CBM-DL-238	47.96^{ef}	3576.46^{l}	4.058^{h}	76.71^{defgh}	46.132^{cd}	41.817^{a}	0.286^{b}	6.654^{bc}	20.45^{a}	11^{e}	31.5^{cde}	37.036^{c}	143.813^{e}
CBM-DL-289	52.23^{abcd}	5503.91^{h}	5.996^{e}	79.765^{bcdef}	63.005^{a}	36.75^{bc}	0.252^{cd}	5.781^{de}	15.35^{h}	12^{de}	25.5^{gh}	44.628^{a}	143.593^{e}
CBM-DL-313	44.88^{f}	3470.08^{op}	3.954^{h}	83.325^{abcd}	48.975^{c}	35.104^{c}	0.24^{d}	5.298^{f}	18.9^{c}	17^{a}	26.5^{fgh}	40.938^{b}	164.277^{c}
CBM-DL-322	53.57^{abc}	2983.03^{q}	3.418^{i}	86.12^{ab}	62.801^{a}	37.12^{bc}	0.295^{b}	5.646^{def}	19.5^{b}	14^{bc}	38.5^{a}	34.15d^{e}	184.066^{b}
CBM-DL-333	48.62^{def}	4415.83^{k}	5.039^{g}	85.41^{abc}	41.798^{de}	34.137^{c}	0.232^{de}	4.718^{g}	18.35^{d}	14^{bc}	33^{bcd}	43.929^{a}	193.586^{a}
CBM-DL-360	49.75^{cde}	5971.15^{e}	6.516^{d}	81.075^{abcde}	26.179^{g}	41.343^{a}	0.333^{a}	4.338^{g}	16.65^{g}	13^{cd}	31.5^{cde}	37.473^{c}	152.359^{d}
CBM-DL-435	47.22^{ef}	6153.81^{d}	6.956^{bc}	77.345^{cdefg}	31.414^{f}	41.675^{a}	0.23d^{e}	4.317^{g}	17.2^{ef}	12^{de}	31.5^{cde}	43.441^{a}	157.305^{d}
CBM-DL-448	51.23^{bcde}	6374.93^{b}	7.224^{b}	68.335^{h}	48.077^{c}	40.645^{ab}	0.335^{a}	5.473^{ef}	18.3^{d}	18^{a}	36.5^{ab}	31.512^{f}	196.943^{a}
UMI 1200	55.77^{a}	3489.9^{n}	3.982^{h}	77.565^{bcdefg}	24.428^{g}	27.713^{d}	0.327^{a}	4.435^{g}	13.55^{j}	12^{de}	28.5^{defgh}	31.787^{f}	108.116^{h}
UMI 1230	51.22^{bcde}	5231.87^{i}	5.686e^{f}	74^{efgh}	23.757^{g}	36.732^{bc}	0.341^{a}	5.882^{de}	11.2^{k}	12^{de}	24^{h}	25.136^{g}	71.472^{i}
CV	3.82	0.1	2.919	5.154	4.918	5.31	4.46	3.389	1.47	5.569	6.998	2.728	1.915
CD @ 0.05	4.147	10.754	0.35	8.61	4.721	4.132	0.025	0.416	0.533	1.639	4.553	2.107	5.994

CC: Chlorophyll content (spad units), LA: Leaf area (cm2), LAI: Leaf area index, RWC: Relative water content, LOV: Leaf orientation value, PR: Photosynthetic Rate (ɥmol m-2s-1), Stomatal conductance (mol H2O m-2s-1), TR: Transpiration rate (mmol H2O m-2s-1), CL: Cob length (cm), NK/R: Number of kernels per row, NKR: Number of kernel rows, SPY: Single plant yield (gm), 100 KW: 100 Kernel weight (gm).

In terms of 100-kernel weight, CBM-DL-289 (44.62 g), CBM-DL-333 (43.92 g), and CBM-DL-435 (43.44 g) recorded the highest values, demonstrating superior seed development. Conversely, UMI 1230 registered the lowest 100-kernel weight at 25.14 g. Cob length also varied significantly across genotypes, with CBM-DL-164 producing the longest cobs (20.7 cm), whereas UMI 1230 had the shortest (11.2 cm), further reinforcing the performance gap between selected inbreds and checks. Interestingly, our findings showed no evidence of yield depression in these genotypes. On the contrary, they performed comparably or even better than the standard checks (UMI 1200 and UMI 1230), with genotypes like CBM-DL-448 and CBM-DL-164 achieving yields close to 200 g per plant. This supports the idea that it is possible to breed for drought tolerance without compromising performance in favorable environments, a goal that has been emphasized in recent breeding strategies (Cairns & Prasanna, 2018; Messina et al., 2015). In terms of chlorophyll content, UMI 1200 unexpectedly recorded the highest SPAD value at 55.77, suggesting a high level of greenness and chlorophyll concentration under irrigated conditions. On the other hand, CBM-DL-238 registered the lowest chlorophyll content at 47.96 SPAD units, despite its high photosynthetic rate, suggesting that factors other than chlorophyll concentration may be contributing to its photosynthetic efficiency. Variation in leaf area and leaf area index (LAI) was also prominent among the evaluated inbred lines. CBM-DL-111 recorded the largest leaf area (7339.8 cm^2), indicating a higher potential for light capture and photosynthesis. In contrast, CBM-DL-313 had the smallest leaf area (3470.08 cm^2). The genotypes with lower LAI could be better suited for drought-prone environments due to reduced transpiration surface (Hammer et al., 2009). From the overall results, the inbred CBM-DL-448 has formed well under both irrigated and drought stress condition and can be serves as the potential parents for the development of drought tolerant maize hybrids.

CONCLUSION

This study successfully identified a subset of maize inbred lines exhibiting superior drought tolerance, characterized by shorter anthesis-silking intervals, higher grain yield, and favorable physiological traits such as high chlorophyll content and efficient water use under stress. Notably, these genotypes also maintained good performance under well-watered conditions, indicating their potential for stable yield across diverse environments without significant yield penalties. These findings provide a valuable foundation for breeding programs aimed at developing drought-resilient maize hybrids, and the selected lines can be further utilized for combining ability studies and marker-assisted selection to accelerate genetic gains in drought tolerance.

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