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Research Article

Genetic Divergence of Maize Hybrids to Drought Tolerance in Response to Pheno-Physiology and Drought Indices Leading to Grain Yield

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Abstract

In an effort to identify drought-tolerant varieties, four important maize hybrids were studied to evaluate their genetic divergences in response to pheno-physiology, yield and drought indices under water deficit stress (WDS). The experiment consisted of two factors and was laid out in a split-plot design with three replications. Two water regimes (well watered and water deficit stress) were applied as the main plot treatments and four maize hybrids (BARI hybrid maize-9, BARI hybrid maize-15, BARI hybrid maize-16 and BWMRI hybrid maize-2) were split over water treatments as sub-plot treatments. The interaction impact of water regimes and maize varieties considerably influenced pheno-physiological traits as well as yield traits of maize, where WDS meaningfully declined the investigated physiological and yield attributes at different magnitudes, except the proline content. Among four hybrids, BWMRI hybrid maize-2 was found to perform better with less reduction percentage, whereas BARI hybrid maize-9 showed the lowest performance with more reduction percentage in terms of the studied traits to WDS. BWMRI hybrid maize-2 showed greater aptitude to hold water in the leaf and better steadiness of chlorophyll content and SPAD value of the leaf under stress than the other three varieties. After all, BWMRI hybrid maize-2 produced the maximum grain yield at both well watered and WDS conditions (13.78 t ha^{-1} and 12.85 t ha^{-1}, respectively) with DSI value 0.78; on the contrary, BARI hybrid maize-9 produced the lowest grain yield (12.21 t ha^{-1} and 11.02 t ha^{-1}, respectively) with DSI value 1.13. Based on pheno-physiological and yield responses as well as tolerance and susceptibility indices of maize hybrids to WDS, BWMRI hybrid maize-2 was identified as comparatively tolerant and BARI hybrid maize-9 as sensitive, whereas BARI hybrid maize-15 and BARI hybrid maize-16 were found as moderately tolerant to drought.

Introduction

Maize (*Zea mays* L.) is considered one of the major cereals contributing as food and forage worldwide and is grown in tropical, subtropical and temperate regions of the world (Sahoo et al., 2021). Maize act as a vital component for various industrial products, along with supplying food for humans, feed and fodder for animals and fuel for domestic use (Hossain et al., 2016). Globally, maize plays a vital role in maintaining food security by feeding millions of people (El-Naggar et al., 2020) with a production of 1.22 billion metric tons on a cultivated area of 82.9 million acres (USDA, Corn Production, 2024).

In Bangladesh, maize is the third most important cereal after rice and wheat with an annual production of 4.95 million tons in 2023, reached up 2.06% from 2022 (BBS, 2024). As a queen of cereal, maize is gaining popularity every day and farmers are shifting to maize cultivation from rice and wheat due to the low cost of production, higher profitability, high demand in the poultry industry and less risk-averse crops (Kausar and Alam, 2016). The production of maize in Bangladesh is increasing rapidly due to its growing demand, but still, now, there is a huge gap between demand and supply, leading to imports to meet the country's demand (Islam and Hoshain, 2022).

In the Asian tropics, about 80% of maize is grown as rain-fed crop (Zaidi et al., 2016) in drought-prone and typical environments (Khandoker et al., 2018) where erratic rainfall impacts maize yields. Under moisture-

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deficient stress condition, maize yield is lower but its production cost is higher than in normal areas due to the high cost of irrigation, labor and other required inputs. Among different abiotic stresses, water deficiency or drought is very incompatible with plant growth and development, leading to considerable losses in crop yield worldwide (Javaid et al., 2023). Rapidly changing climate is causing an increase in desertification that leads to drought problems (FAO, 2021), which severely affects the production of cereal crops like wheat and maize (Mazhar et al., 2021).

Drought greatly affects the yield processes by affecting the vegetative and reproductive stages, resulting in final yield losses of maize (Javaid et al., 2023; Beyene et al., 2017). Drought can occur at any stage of maize growth, but the most sensitive stages for water scarcity are the flowering and grain-filling periods (Meseka et al., 2013). Water scarcity affects the maize crop through poor germination, stunted growth, top firing, tassel blast, and finally, reduced grain yields up to 40% (Javaid et al., 2023; Kim et al., 2019) with a maximum effect during early ovary and kernel development (Oury et al., 2016).

Maize breeders and growers are facing major challenges to sustain maize productivity under changing climatic conditions. In this context, proper action is needed to face the problem and drought-tolerant varieties might be an effective way to sustain the maize production under drought condition. Researchers are working to adopt tolerant hybrid maize varieties for drought-prone areas in order to improve sustainable maize cultivation (Koirala et al., 2021). Developing of drought-tolerant maize hybrids or selecting tolerant varieties from the existing genotypes would be an effective strategy to minimize the drought-caused yield losses in maize. In that case, screening of drought-tolerant maize hybrids with high yield potential from the existing released varieties would be one of the effective approaches to combat the adverse effects of drought as well as to sustain maize productivity under changing climatic condition. In the present research, four novel maize hybrids were evaluated for drought tolerance based on their pheno-physiological traits and drought indices, leading to grain yield to identify comparatively drought-tolerant maize hybrid(s).

Materials and Methods

Experimental duration and site

The experiment was implemented from December, 2023 to May 2024 at the research field of Crop Physiology and Ecology Department, Hajee Mohammad Danesh Science and Technology University, Dinajpur, 5200, Bangladesh located between 25º39′ N latitude and 88º41′ E longitude with an elevation of 37.58 m above the sea level.

Soil and climatic data of the experimental site

The experimental field is a medium-high land belonging to the non-calcareous dark grey floodplain soil with a sandy loam texture. The physical and chemical properties of the soil of the experimental field are tabulated in Table 1. The area faces a subtropical climate characterized by rainfall during the month of last April to October and scanty rainfall during December. The weather conditions during the crop growing period are presented in Figure 1.

Table 1. Physical and chemical properties of the soil of the experimental field

Physical properties	Value	
Particle size (%)		
Sand (2-0.02 mm)	59.00	
Silt (0.02–0.002 mm)	29.00	
Clay (<0.002 mm)	13.80	
Bulk density (g cm^{-3})	0.84-1.16	
Textural class	Sandy loam	
Chemical properties	**Analytical value**	**Interpretation**
pH	5.28	Moderately acidic
Organic carbon (%)	1.03	Low
Organic matter (%)	1.83	Low
Total N (%)	0.085	Very low
Available P (µg/g)	41.38	Medium
Exchangeable K (meq/100 g soil)	0.34	Medium low

Source: Soil Resource Development Institute, Dinajpur, Bangladesh

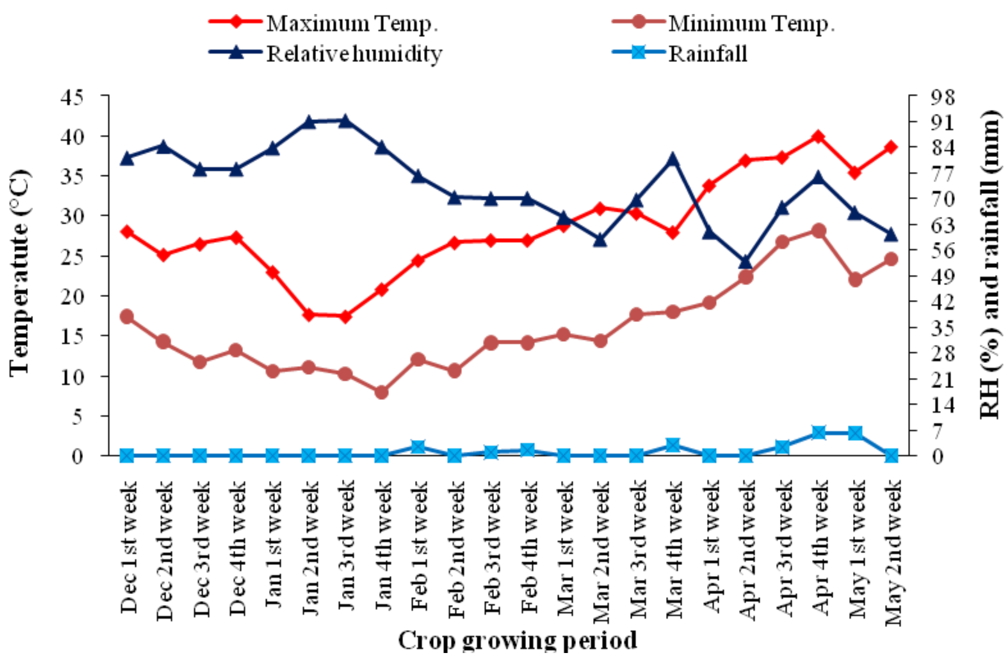

Figure 1. Weekly average weather data during the maize growing season (2023-24).
Source: Meteorological Observatory, Bangladesh Meteorological Department, Rajbati, Dinajpur.

Source and acquaintance of the plant materials

Four maize hybrids (BARI Hybrid Maize-9, BARI Hybrid Maize-15, BARI Hybrid Maize-16 and BWMRI Hybrid Maize-2) were collected from Bangladesh Wheat and Maize Research Institute (BWMRI), Nashipur, Dinajpur, Bangladesh. The salient features of the plant materials are shown in Table 2.

Table 2. Salient features of the maize hybrids evaluated for drought tolerance

Maize hybrids	Developed by	Year of release	Major characteristics	Available at the link
BARI Hybrid Maize-9	BARI	2007	Single cross hybrid, duration: 105-150 days, plant height: 205-230 cm, ear length: 100-115 cm, 1000 grain weight: 340-360 g, Yield: 11.50-12.50 t ha^{-1}	https://bwmri.gov.bd/site/page/c6a71195-3bae-4d57-aab3-7da8d8d02b6e
BARI Hybrid Maize-15	BARI	2017	Single-cross high-yielding hybrid, duration: 121-148 days, plant height: 165-214 cm, ear length: 100-105 cm, 1000 grain weight: 360-380 g, Yield: 12.07- 12.75 t ha^{-1}, high heat tolerant	https://bwmri.gov.bd/site/page/9ce1d7f6-d05d-42ba-890e-3963c8660237
BARI Hybrid Maize-16	BARI	2018	Single-cross hybrid, duration: 140-145 days, plant height: 180-190 cm, ear length: 80-85 cm, 1000 grain weight: 420-430 g, Yield: 10.00-11.57 t ha^{-1}, salt tolerant	https://bwmri.gov.bd/site/page/b25f533f-8feb-43f1-9160-939596ac5456
BWMRI Hybrid Maize-2	BWMRI	2022	Single-cross hybrid, plant height: 220-240 cm, ear length: 100-130 cm, 1000 grain weight: 400-460 g, Yield: 12.00-14.00 t ha^{-1}	https://bwmri.gov.bd/site/page/9c4f7124-56a0-420d-a427-f82b77647fef

Experimental design, layout and treatments

The experiment was designed in a split plot manner with three replications. The unit plot size was 3 m × 2 m having a plot to plot and block-to-block distance of 0.75 and 1 m, respectively. Two water regimes (well watered and water deficit stress) were placed in main plots as main plot treatments and four maize hybrids (BARI Hybrid Maize-9, BARI Hybrid Maize-15, BARI Hybrid Maize-16 and BWMRI Hybrid Maize-2) were placed randomly in subplots as subplot treatments.

Stress treatment through the regulation of irrigation water

After seed sowing, slight irrigation was supplied to all plots to facilitate the successful germination of seeds and proper seedling establishment. Thereafter, well watered plots were irrigated thrice at 8-10 leaf stage (40 DAS), tasseling stage (75 DAS) and grain filling stage (105 DAS), while no irrigation was given to stressed plots throughout the growing season.

Production technology

The experimental plots were prepared through good ploughing, laddering, harrowing and levelling followed by the removal of weeds and stubbles. Each plot was fertilized with urea, triple superphosphate, muriate of potash, gypsum, zinc sulphate, boric acid and well-decomposed cow dung as described in Table 3. Seeds were sown in lines maintaining the spacing of 70×20 cm at a depth of approximately 1 inch from the soil surface. The crop was kept weed free through necessary weeding and earthing up of the rows of crops was made after the application of the second instalment of urea. Plant protection measures were taken during the growing season to guard the crop from several pests and diseases.

Table 3. Description of fertilizers and their methods of application

Name of fertilizers	Available nutrient	Rate of fertilizer (kg ha^{-1})	Rate of fertilizer (g $plot^{-1}$)	Methods of application
Urea	N	550	330	1/2 urea as a basal dose and rest as top dressed at 78 DAS
Triple superphosphate	P	280	168	Full amount as a basal dose
Muriate of potash	K	210	126	Full amount as a basal dose
Gypsum	S	222.5	133.5	Full amount as a basal dose
Zinc sulphate	Zn	13.5	8.1	Full amount as a basal dose
Boric acid	B	6.5	3.9	Full amount as a basal dose
Cow dung	-	4.5 t ha^{-1}	2.7 kg ha^{-1}	Full amount as a basal dose

Data collection

Data were recorded on soil moisture content, phenophases, physiological traits, yield attributes and drought indices.

Soil moisture content

Soil moisture content was measured according to Ray et al., (2020b) and the moisture content was calculated on dry weight basis using the following formula-

$$\text{Soil moisture content } (\%) = \frac{\text{Fresh weight of soil} - \text{Weight of oven dry soil}}{\text{Weight of oven dry soil}} \times 100$$

Days to different phenophases

Days required to attain different phenophases viz., seedling emergence, tasseling, silking and harvest maturity were recorded in days when 50% of plants of each plot reached a definite phenophase.

Measurement of physiological variables

Membrane injury index

Cell membrane injury index was determined at tasseling stage according to Kocheva et al., (2014) using the formula, I (%) = [1- (1- D_1/D_2)/ (1-C_1/C_2)] × 100; where, D_1 and D_2 represent the conductivity of treated samples after 24 hours of incubation and after tissue killing, respectively and C_1 and C_2 are the corresponding values for the control.

Relative leaf water content

Relative leaf water content (RLWC) was determined at tasseling stage according to Kocheva et al., (2014) using the formula below-

$$RLWC\ (\%) = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \times 100$$

Chlorophyll content

Total chlorophyll of the leaf was estimated at tasseling stage according to Witham et al., (1986) using the formula; total chlorophyll (mg g^{-1} FW) = [20.2(D_{645}) +8.02(D_{663})] x [V/ (1000 x W)], Where, V = Volume of 80% aqueous acetone (ml), W = Weight of fresh leaf (g), D_{645} = Absorbance at 645nm wavelength and D_{663} = Absorbance at 663nm wavelength.

SPAD value

The SPAD value of the leaf was estimated at tasseling stage with the help of a SPAD meter (Model: SPAD-502, Minolta Co. Ltd, Japan).

Proline content

The proline content of the leaf was quantified at tasseling stage according to Bates, (1973) from a standard curve and calculated on a fresh weight basis using the following formula-

µ moles proline / g of fresh plant material = {(µ g proline / ml× ml toluene) / 115.5 µ g / µ moles} / (g sample/5).

Yield and yield components

Yield contributing traits *viz.* number of fertile cobs plant^{-1}, number of rows cob^{-1} and single cob weight were recorded properly after final harvest. Grains were adjusted to 10% moisture by sun drying and then grain weight cob^{-1}, 100-grain weight and grain yield (t ha^{-1}) were measured and recorded properly.

Calculation of drought tolerance and susceptibility indices

Drought tolerance index was calculated according to Goudarzi and Pakniyat, (2008) using the formula; Drought tolerance index (DTI) = Ys ÷ Yp; where Ys and Yp are the mean values of genotypes under stress and non-stress conditions, respectively.

Drought susceptibility index (DSI) was calculated for grain yield as described by Fisher and Maurer, (1978) using the formula; DSI = $(1- Y/Y_p) / (1- X/X_p)$; Where, Y = Grain yield of maize in the stress environment, Y_p = Grain yield of maize in the stress-free environment, X = Mean Y of all maize varieties and Xp = Mean Y_p of all maize varieties.

Statistical analyses

The collected data were analyzed by partitioning the total variance with the help of a computer software STATA (Small Stata 12.0) program to establish the ANOVA. The treatment means were compared using Tukey's test at 5% level of probability.

Results and discussion

Soil moisture content

The soil moisture content at 0-15 cm depth of well watered and water deficit stressed plots during the emergence, tasseling, and harvesting stages of seedlings is displayed in Figure 2. It shows that, at the stages of seedling emergence, tasseling, and harvesting, well watered plots maintained higher soil moisture levels (34.33, 23.85 and 18.56%, respectively) than that of water deficit stressed plots (32.66, 13.69, and 6.42%, respectively). Additionally, this figure illustrates how soil moisture in water deficit stressed plots rapidly decreased as time passed after seeding. Soil moisture was found to be roughly the same at the seedling emergence stage under both well watered and drought situations. However, there was a greater difference in soil moisture at well watered and water deficit stressed situations during the tasseling and harvesting stages. This fluctuation at different phases may be caused by precipitation during the early stages of maize growth, which lowers the rate of evapotranspiration because of decreased temperature and sunlight (Ali et al., 2018). However, as time went on, there was no precipitation, and the temperature rose as a result of greater sunlight, which caused the soil to lose more water through evapotranspiration. It could possibly be because plants use relatively less water in their early growth phases than they do in their later growth and maturity stages (Ray et al., 2020b). Deficit-irrigation allocation thereby caused the crop to experience stress during the reproductive phases but little to no stress during the vegetative stages, which ultimately impacted the crop's morphology, physiology, and production. Other previous researches also revealed remarkable variation in soil moisture content of well watered and water deficit stressed plots of wheat (Sindabad et al., 2023; Jannat et al., 2023; Haque et al., 2022), maize (Haque et al., 2021) and mung bean (Ahmed et al., 2021).

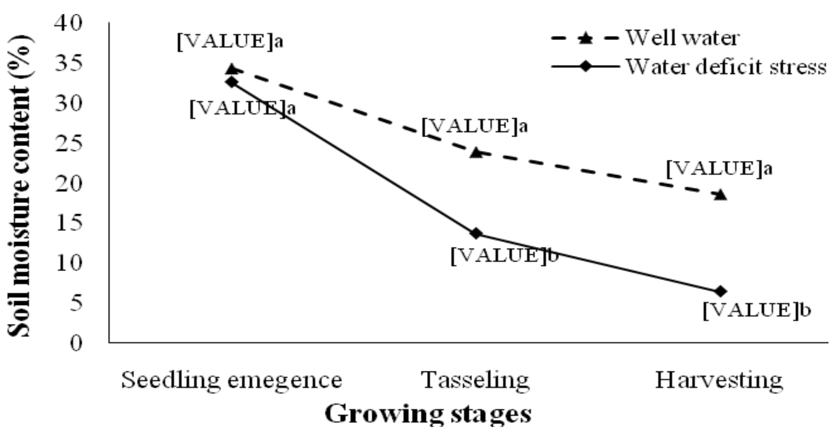

Figure 2. Soil moisture content (0-15 cm depth) at different growing stages of maize as influenced by water regimes.

At each definite stage, means having similar letter(s) did not differ significantly at the P5% level according to the Tukey's test.

Days to phenophases

Table 4 shows that the days to silking and maturity were significantly affected by the interaction between water regimes and maize hybrids. For each variety, a specific number of days were needed to reach particular phenophases. Under water deficit stress condition, BARI hybrid maize-9 and BARI hybrid maize-15 required an equal number of days as well watered condition but BWMRI hybrid maize-2 required one day more and BARI hybrid maize-16 required one day less to emergence. Under well watered condition, the requirement of days to tassel emergence was 83 in BARI hybrid maize-9, 82 in BARI hybrid maize-15, 78 in BARI hybrid maize-16 and 85 in BWMRI hybrid maize-2, whereas under stress condition, the durations were 78 days for both BARI hybrid maize-9 and BARI hybrid maize-15, 81 days for BARI hybrid maize-16 and 83 days for BWMRI hybrid maize-2. At water deficit stress condition, all the varieties required fewer days to silking (83 to 87 days) compared to well watered condition (85 to 92 days). Under water deficit stress condition, all the varieties attained maturity earlier compared to the well watered condition. Under stress condition, harvest maturity occurred 2 days earlier in BARI hybrid maize-9, 4 days earlier in BARI hybrid maize-16 and 3 days earlier in both BARI hybrid maize-15 and BWMRI hybrid maize-2. A similar phenological response was also observed by Pramanik et al., (2022a) and Ali et al., (2018) in wheat and Ray et al., (2020a) in maize. They noticed that, under water deficit stress, wheat crop attained their different phenophases earlier as compared to well watered and the earliness was different in different genotypes according to their genetic variability that support our present findings.

Table 4. Number of days required to attain different phenophases of maize varieties as influenced by water regimes

Maize varieties	Number of days (mean± standard error) required to attain							
	Seedling emergence		Tasseling		Silking		Harvest maturity	
	WW	WDS	WW	WDS	WW	WDS	WW	WDS
BARI Hybrid Maize-9	8±0.28	8±0.50	83±2.33	78±2.66	87±1.66cd	85±2.00de	135±2.33bc	133±3.42c
BARI Hybrid Maize-15	7±0.33	7±0.50	82±2.50	78±1.63	90±2.33ab	86±1.86cd	139±2.66ab	136±3.67bc
BARI Hybrid Maize-16	9±0.66	8±0.37	78±1.66	81±2.33	85±1.93de	83±2.33e	134±3.11bc	130±2.92e
BWMRI Hybrid Maize-2	8±0.45	9±0.49	85±2.55	83±2.83	92±3.11a	87±1.68bc	142±3.34a	139±3.21ab
F test (0.05)	NS		NS		0.05		0.01	
CV (%)	4.52		6.17		5.65		5.32	

In the column of the respective phenophase, means with similar letter(s) did not differ significantly at the p≤5% level according to the Tukey's test. NS, indicates non-significant at P ≤ 5% level of probability. WW = Well watered, WDS = Water deficit stress.

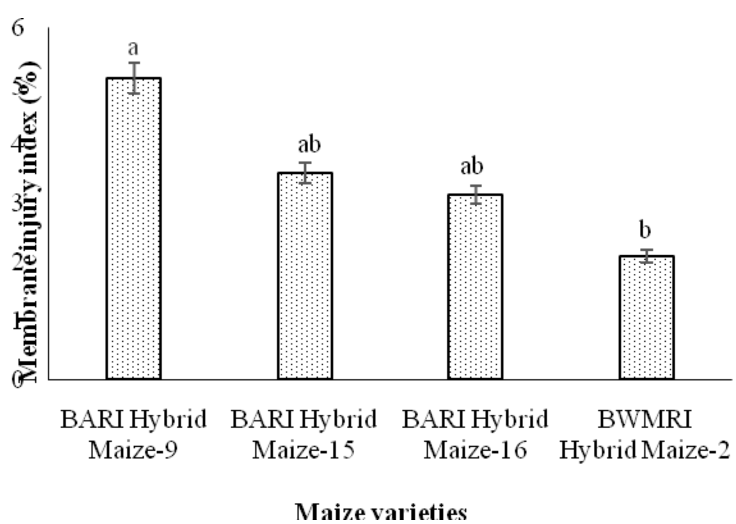

Figure 3. Membrane injury index of maize varieties at tasseling stage under water deficit stress condition.
Vertical bars indicate the standard error (±). Means having similar letter(s) did not differ significantly at the P5% level according to the Tukey's test.

Membrane index injury

Figure 3 indicates that, among the four maize hybrids, BARI hybrid maize-9 showed the highest injury index (5.13%), which confirms more disturbances in membrane permeability and less tolerance capacity of the variety against drought. On the other hand, BWMRI hybrid maize-2 had the lowest injury index (2.10%), suggesting less pronounced membrane damage and comparatively less susceptibility to drought stress. BARI hybrid maize-15 and BARI hybrid maize-16 showed moderate disturbance in membrane permeability (3.51 and 3.15%, respectively) under water deficit condition. Researchers enacted that cell membrane stability has been extremely used as a selection criterion for abiotic stress tolerance against drought and high temperature in wheat (Bajji et al., 2001). These results are in agreement with Kocheva et al., (2014), who revealed that the genotypes with less injury to plasma membranes are tolerant as compared to the genotypes with more injury to cell membranes. Goodarzian-Ghahfarokhi et al., (2016)'s findings corroborate those of the current investigation and reported that the tolerant maize experienced less membrane disruption from water deficiency than the susceptible variety. Water deficit-mediated differential membrane injury was also reported in wheat (Pramanik et al., 2022a; Jannat et al., 2023) and in maize (Ray et al., 2020b) which are in line with the present results.

Physiological traits

The analysis of variance in the physiological traits of maize leaves reveals that these traits were significantly influenced by the interaction effects of water regimes and maize varieties except proline content (Table 5). Results show that the adverse effects of water deficit stress led to a notable decline in the relative leaf water content, chlorophyll content and SPAD value, but an increase in the proline content of the maize leaves. Genetical variation was observed in maize hybrids in their physiological responses with respect to drought. The maximum reduction (23.71%) in RLWC was detected in BARI hybrid maize-9 as compared with unstressed plants. Other three varieties, BARI hybrid maize-15, BARI hybrid maize-16 and BWMRI hybrid maize-2 showed 6.14%, 22.66% and 2.33% decreases in their RLWC, respectively due to water deficit stress condition. The most pronounced reduction in chlorophyll content was found in BARI hybrid maize-9 (28.57%), whereas BWMRI hybrid maize-2 showed the lowest reduction (9.56%) followed by BARI hybrid maize-16 (13.74%) and BARI hybrid maize-15 (15.79%). Water deficit stress reduced the SPAD value by 18.73% in BARI hybrid maize-9, 10.98% in BARI hybrid maize-15, 15.15% in BARI hybrid maize-16 and 5.75% in BWMRI hybrid maize-2. On the other hand, the proline content of maize leaf was increased by 5.69%, 14.25%, 9.34% and 42.34% in BARI hybrid maize-9, BARI hybrid maize-15, BARI hybrid maize-16 and BWMRI hybrid maize-2, respectively under water deficit stress as compared with unstressed plants.

Table 5. Physiological traits (mean ± SE) of maize varieties at the tasseling stage as influenced by water regimes

Maize varieties	Water regimes	Relative leaf water content (%)	Total leaf chlorophyll content (mg g^{-1} FW)	SPAD value of leaf	Proline content of leaf (µmole g^{-1} FW)
BARI Hybrid Maize-9	Well watered	76.75±2.78bc	2.38±0.31a	51.26±1.67ab	3.34±0.23
	Water deficit stress	58.55±1.47d	1.70±0.23d	41.66±1.18c	3.53±0.22
BARI Hybrid Maize-15	Well watered	83.66±2.65a	1.52±0.27d	54.30±2.13a	3.79±0.32
	Water deficit stress	78.52±2.83ab	1.28±0.22e	48.34±1.66b	4.33±0.34
BARI Hybrid Maize-16	Well watered	81.27±3.13ab	2.11±0.26bc	53.33±1.74ab	3.96±0.37
	Water deficit stress	62.85±1.88cd	1.82±0.19cd	45.25±1.83bc	4.33±0.41
BWMRI Hybrid Maize-2	Well watered	84.35±3.37a	2.51±0.25a	55.34±1.79a	3.85±0.39
	Water deficit stress	82.38±3.14ab	2.27±0.24ab	52.16±1.54ab	5.48±0.33
F test (0.05)		0.01	0.01	0.05	NS
CV (%)		9.33	7.31	8.50	6.73

In the column means with similar letter(s) did not differ significantly at the p≤5% level according to the Tukey's test. NS, indicates non-significant at P ≤ 5% level of probability. SE indicates standard error.

Results showed that well watered plants had higher relative leaf water content than non-irrigated water-stressed plants and tolerant variety maintained a higher leaf water status compared to susceptible variety. The RLWC is directly related to soil water content imitating the metabolic events in cells and utilized as an utmost significant index for drought tolerance in crop plants (Anjum et al., 2011; Jannat et al., 2023). Reduced ability to retain water in maize leaf under water deficit stress was previously reported by Ray et al., (2020a) that consistent with our findings. In another study, Roy et al., (2025) and Pramanik et al., (2021) stated that crop plants exhibited lesser RLWC at water limiting condition in comparison to normal situations. These findings support the findings of the present investigation. The decline in photosynthetic pigment (chlorophyll) under water-limiting drought situation has been deliberated as a distinctive indicator of oxidative strain that might be the consequence of photo-oxidation and destruction of leaves chlorophyll in crop plants (Keyvan, 2010). In the present study, the chlorophyll content of maize leaf at tasseling was reduced due to water deficit stress, as the plant suffers from severe water deficit stress at this stage. Insufficient soil water declines metabolic activity, reduces biomass accumulation and decreases the rate of photosynthesis by reducing the leaf chlorophyll ultimately leading to a decrease in maize yield (Chang et al., 2008; Zhang et al., 2009; Bu et al., 2010). Results from other studies (Khayatnezhad and Gholamin, 2012; Haque et al., 2021; Haque et al., 2022; Pramanik et al., 2021) also notify chlorophyll reduction in cereal crops due to water deficit which is consistent with the findings of our present investigation. Drought stress can cause reactive oxygen species (ROS) to be produced, which can damage the leaf cells and chlorophyll, resulting in a decrease in leaf greenness (Begum et al., 2019). Allen and Ort, (2001) previously mentioned that drought stress has a direct impact on the photosynthetic apparatus, by hampering major components of photosynthesis like the thylakoid electron transport, the carbon reduction cycle and the stomatal control of the CO_2 supply. Molla et al., (2023) clarified that the SPAD values decreased, as the water deficit stress duration increased. The outcomes of the current investigation are corroborated by these studies. Proline plays a role as an enzyme stabilizing agent that regulates and reduces water loss from the cell under water deficit circumstances and it has the capability to conciliate osmotic regulation and attributes to substantial sub-cellular configuration (Jannat et al., 2023). In the present study, the proline level was increased in maize leaf and the tolerant variety had the maximum increment indicating more osmoregulation capacity. Saad-Allah et al., (2022) and Kumdee et al., (2023) reported that proline content increases in maize hybrids under the longest irrigation interval and water deficit which is aligned with our research findings.

Yield components and yield

Table 6 denotes that, significant variation was found in single cob weight, grains weight cob^{-1}, 100-grain weight and grain yield of maize due to the interaction effect of water regimes and maize varieties but the effect was non-significant on fertile cobs plant^{-1} and rows cob^{-1}. Water deficit stress caused a meaningful reduction in yield components and yield of maize, where genotypical divergences of maize hybrids were noticed in their reduction magnitudes. In the case of fertile cobs plant^{-1}, the most decrease (21.05%) was found in BARI hybrid maize-15 as compared with unstressed plants. The other three varieties, BARI hybrid maize-9, BARI hybrid maize-16 and BWMRI hybrid maize-2 decreased in their number of fertile cobs plant^{-1} by 15.58%, 16.25% and 14.55%, respectively due to water deficit stress. In comparison to unstressed plants, stressed plants of BARI hybrid maize-9 showed the most noticeable degradation (14.86%) in rows cob^{-1}, while BWMRI hybrid maize-2 showed the least decline (11.06%). The degree of reduction was rather moderate (12.38% in BARI hybrid maize-15 and 12.70% in BARI hybrid maize-16). In the case of single cob weight, the most decline (11.80%) was found in BARI hybrid maize-9 as compared with unstressed plants. The other three varieties, BARI hybrid maize-15, BARI hybrid maize-16 and BWMRI hybrid maize-2 decreased in their cob weight by 9.02, 9.16 and 5.06%, respectively due to water deficit stress condition. The most distinct deterioration (13.10%) in grain weight cob^{-1} was recorded in stressed plants of BARI hybrid maize-9 as compared to unstressed plant, while the least reduction (10.08%) was calculated in BWMRI hybrid maize-2. The degree of reduction was 11.61% in BARI hybrid maize-15 and 12.55% in BARI hybrid maize-16 which were comparatively moderate than that of the other two varieties. Among four varieties, BARI hybrid maize-9 caused the maximum drop (15.50%) in 100-grain weight and BWMRI hybrid maize-2 caused the minimum (7.74%), whereas BARI hybrid maize-15 (12.23%) and BARI hybrid maize-16 (13.30%) performed moderate reduction under stress condition. Water deficit stress mediated maximum reduction in grain yield (9.75%) was observed in BARI hybrid maize-9 which indicates more sensitivity to drought and followed by BARI hybrid maize-16 (8.65%) and BARI hybrid maize-15 (8.12%), while BWMRI hybrid maize-2 gave least decline (6.75%) in its grain yield indicating less susceptible to water deficit stress. However, under both well watered and water deficit stress conditions, BWMRI hybrid maize-2 achieved the highest grain yield (13.78 tha^{-1} and 12.85 tha^{-1} respectively), while BARI hybrid maize-9 produced the lowest grain yield (12.21 tha^{-1} and 11.02 tha^{-1}, respectively). The results of the research showed that water deficit stress had a substantial impact on the phenology and physiology of the crop, which in turn led to a rash drop in yield traits and yield. Compared to drought-stressed maize, plants cultivated with enough water generated higher single cob weight, grain weight cob^{-1} and more 100-grain weight, which resulted in higher matter accumulation and grain yield. Under drought stress, the overproduction of ROS (H_2O_2 and O_2) may have contributed to the declines in yield and yield components by oxidatively damaging membranes and lipids and raising MDA levels (Ramadan et al., 2021). Insufficient soil water weakens the metabolic activity of maize, reduces its biomass accumulation, and decreases its photosynthetic rate eventually leading to a decrease in maize yield (Bu et al., 2010). Our findings are in line with other research showing that plants exhibited a substantial decline in yield components (Suralta et al., 2010) and a drop in grain yield (Hugh and Richard, 2003; Pervez et al., 2004) as moisture stress increased.

Table 6. Yield components and yield (mean ± SE) of maize varieties as influenced by water regimes

Maize varieties	Water regimes	Fertile cobs plant^{-1}	Rows cob^{-1}	Single cob weight (g)	Grain weight cob^{-1} (g)	100-grain weight (g)	Grain yield (t ha^{-1})
BARI Hybrid Maize-9	Well watered	1.54±0.013	16.28±0.28	264.56±5.76b	185.75±3.33c	28.58±1.91d	12.21±0.19d
	Water deficit stress	1.30±0.024	13.86±0.26	233.33±4.32d	161.42±2.66f	24.15±1.27f	11.02±0.15f
BARI Hybrid Maize-15	Well watered	1.71±0.022	17.45±0.34	271.79±5.89ab	194.31±3.68b	33.35±1.85b	12.44±0.21c
	Water deficit stress	1.35±0.034	15.29±0.52	247.28±5.11c	171.75±3.94d	29.27±1.74d	11.43±0.14e
BARI Hybrid Maize-16	Well watered	1.60±0.023	16.53±0.33	266.67±6.33b	190.44±4.13b	31.57±1.79c	12.48±0.19c
	Water deficit stress	1.34±0.019	14.43±0.29	242.23±4.96cd	166.54±2.84e	27.37±1.23e	11.40±0.15e
BWMRI Hybrid Maize-2	Well watered	2.13±0.026	18.62±0.42	276.55±6.24a	203.91±4.25a	36.16±1.88a	13.78±0.26a
	Water deficit stress	1.82±0.027	16.56±0.33	262.56±6.10ab	183.35±3.83c	33.36±1.81b	12.85±0.33b
F test (0.05)		NS	NS	0.01	0.01	0.01	0.05
CV (%)		6.68	3.81	6.82	4.65	7.54	6.79

In the column means with similar letter(s) did not differ significantly at the p≤5% level according to the Tukey's test. NS, indicates non-significant at P ≤ 5% level of probability. SE indicates standard error.

Drought tolerance index

Table 7 presents the drought tolerance indices of maize hybrids based on several physiological and yield traits. Calculated values unveil that, the varieties showed notable genetic variation in giving their varying levels of drought resistance as shown by the drought tolerance indices. The drought tolerance indices were 0.7629, 0.7142, 0.8127, 1.0568, 0.8441, 0.8513, 0.8819, 0.8690, 0.8449 and 0.9025 in BARI hybrid maize-9; 0.9386, 0.8421, 0.8902, 1.1424, 0.7894, 0.8762, 0.9098, 0.8839, 0.8776 and 0.9188 in BARI hybrid maize-15; 0.7733, 0.8625, 0.8484, 1.0934, 0.8375, 0.8729, 0.9083, 0.8745, 0.8669 and 0.9134 in BARI hybrid maize-16; 0.9766, 0.9043 0.9425, 1.4233, 0.8544, 0.8893, 0.9494, 0.8991, 0.9225 and 0.9325 in BWMRI hybrid maize-2 based on RLWC, TCCL, SPADL, PCL, FCP, RC, SCW, GWC, 100-GW and GY. The varieties with the high tolerance score demonstrated greater resilience under stress than the other varieties with comparatively low tolerance indices. Other researchers (Hooshmandi, 2019; Haque et al., 2021; Pramanik et al., 2022a; Pramanik et al., 2022b; Miajy et al., 2024) also used the stress tolerance index as an important tolerance criterion for plant under stress conditions.

Table 7. Drought tolerance indices of maize varieties based on different traits

Maize varieties	Drought tolerance indices									
	RLWC	TCCL	SPADL	PCL	FCP	RC	SCW	GWC	100-GW	GY
BARI Hybrid Maize-9	0.7629	0.7142	0.8127	1.0568	0.8441	0.8513	0.8819	0.8690	0.8449	0.9025
BARI Hybrid Maize-15	0.9386	0.8421	0.8902	1.1424	0.7894	0.8762	0.9098	0.8839	0.8776	0.9188
BARI Hybrid Maize-16	0.7733	0.8625	0.8484	1.0934	0.8375	0.8729	0.9083	0.8745	0.8669	0.9134
BWMRI Hybrid Maize-2	0.9766	0.9043	0.9425	1.4233	0.8544	0.8893	0.9494	0.8991	0.9225	0.9325

RLWC = Relative leaf water content, SPAD = SPAD value of leaf, TCCL =Total chlorophyll content of leaf, PCL = Proline content of leaf, FCP = Fertile cobs plant^{-1}, RC = Rows cob^{-1}, SCW = Single cob weight, GWC = Grain weight cob^{-1}, 100-GW = 100-grain weight, GY = Grain yield

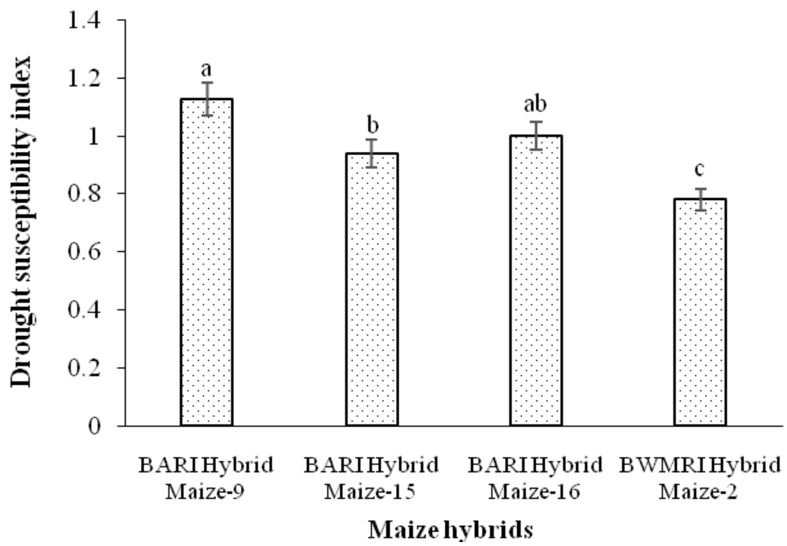

Figure 4. Drought susceptibility index of maize hybrids based on grain yield.
Vertical bars indicate the standard error (±). Means having similar letter(s) did not differ significantly at the P≤5% level according to the Tukey's test

Drought susceptibility index (DSI) based on grain yield

The graphical representation (Figure 4) illustrates the drought susceptibility index of different maize hybrids based on grain yield. The graph demonstrates that BARI hybrid maize-9 had the highest DSI (1.13) which acquainted the variety as most susceptible to drought, whereas BWMRI hybrid maize-2 had the lowest DSI (0.78) which indicates this variety is the most tolerant variety against drought stress. BARI hybrid maize-15 and BARI hybrid maize-16 exhibited moderate DSI (0.94 and 1.00, respectively) which identified them as moderately susceptible varieties to drought. Mwadzingeni et al., (2016) and Pramanik et al., (2021) used the stress susceptibility index as a useful indicator to find the drought-tolerant genotypes under water deficit stress conditions and they concluded that the genotypes with the lowest values are marked as drought-tolerant compared to the genotypes with the highest values of stress susceptibility index.

Conclusion

The overall findings showed that stress caused by water shortage harmed maize's pheno-physiological characteristics, yield attributes and yield. Variety having a greater ability to maintain higher leaf water content, higher leaf chlorophyll, SPAD greenness and proline accumulation as well as better yield performance under water deficit stress indicated the varieties' tolerance to drought. Considering drought tolerance and susceptibility indices based on grain yield, the order of drought tolerance was BWMRI hybrid maize-2 > BARI hybrid maize-15 > BARI hybrid maize-16 > BARI hybrid maize-9. In conclusion, among the studied maize hybrids, BWMRI hybrid maize-2 was found a comparatively drought tolerant variety, while BARI hybrid maize-9 was drought susceptible variety and the other two hybrids (BARI hybrid maize-15 and BARI hybrid maize-16) were accounted as moderately drought tolerant varieties.

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