

RESEARCH ARTICLE

IMPACT OF DROUGHT STRESS ON MORPHOPHYSIOLOGICAL, YIELD, BIOCHEMICAL AND SEED QUALITY OF MUSTARD GENOTYPES IN BANGLADESH

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ABSTRACT

Drought stress severely constraints mustard growth, physiology, yield, and oil quality in Bangladesh, making the identification of drought-tolerant genotypes crucial for sustaining production under climate change. This study was conducted at Shibganj Upazila, Bogura district, Bangladesh, during the 2023-2024 growing season to evaluate morphophysiological, biochemical, yield, and seed quality responses of eight BARI mustard genotypes under well-watered and drought stress conditions. The experiment followed a Randomized Complete Block Design (RCBD) with three replications and two moisture regimes, totaling 48 plots. Data were recorded on plant height, primary branches, leaf area index (LAI), chlorophyll content, proline accumulation, siliques per plant, seeds per silique, silique length, 1000-seed weight, seed and biological yield, harvest index, oil content, and protein content. Drought significantly reduced vegetative growth, photosynthetic pigments, yield components, seed yield, and seed quality, while increasing proline accumulation. BARI Sarisha-16 consistently maintained higher chlorophyll content, proline accumulation, siliques plant⁻¹, 1000-seed weight, and seed yield (1.90 t ha⁻¹ under stress) with the lowest Drought Susceptibility Index (DSI = 0.55), followed by BARI Sarisha-11 and BARI Sarisha-13. In contrast, BARI Sarisha-10 and BARI Sarisha-12 exhibited high susceptibility and lowest yield stability. The findings suggest that BARI Sarisha-16 is a highly drought-tolerant genotype with strong yield stability and seed quality under water-limited conditions. BARI Sarisha-16 should be prioritized for drought-prone mustard-growing regions and considered in future breeding programs for drought tolerance improvement.

KEYWORDS

Mustard (*Brassica rapa*), drought stress, yield, tolerance, genotypes

1. INTRODUCTION

Mustard (*Brassica rapa* L.) is one of the most important oilseed crops grown in Bangladesh, contributing significantly to edible oil supply, rural livelihoods, and agricultural sustainability. The crop plays a vital role in human nutrition by supplying high-quality edible oil rich in unsaturated fatty acids and bioactive compounds such as tocopherols and glucosinolates that promote health and support food security (Rahman et al., 2022 and Hossain et al., 2023). Mustard cultivation is largely concentrated in the northern regions of Bangladesh, where agro-ecological conditions favor its winter-season growth. According to BBS (2022), mustard remains a major oilseed crop in Bangladesh, yet per-capita edible oil demand continues to exceed domestic production. Thus, enhancing mustard productivity through resilient genotypes and improved agronomic management is critical for national food and nutritional security.

Besides, the performance of mustard in Bangladesh is largely dependent on genotype selection, as genotypic variability strongly influences yield potential, phenology, and stress response (Mohan, 2025 and Islam et al., 2024). Breeding efforts by BARI have released several varieties with

improved yield attributes, but climatic stresses remain a major constraint to achieving maximum productivity. Among abiotic factors, drought stress has emerged as a critical challenge, particularly under rainfed conditions in northern Bangladesh, where winter rainfall is extremely limited. Climate projections for Bangladesh predict increased temperature and irregular precipitation, intensifying water scarcity episodes during the mustard-growing period (Devi et al., 2022). Water deficit adversely affects plant growth and physiological functions, leading to reduced crop establishment, nutrient uptake, photosynthetic efficiency, and reproductive development (Singh, 2021). Consequently, drought stress negatively impacts yield and oil accumulation, ultimately reducing farmer income and food supply. Drought induces substantial morphological alterations in mustard, such as reduced plant height, fewer primary branches, smaller leaf area, and compromised canopy development, ultimately limiting assimilate production (Singh et al., 2021 and Sharma et al., 2022). Physiologically, drought stress restricts chlorophyll synthesis and leaf gas exchange capacity, while promoting osmotic adjustment mechanisms including proline accumulation to maintain cellular homeostasis (Zhang et al., 2022 and Alam et al., 2024). Biochemical responses such as enhanced proline, antioxidant activity, and metabolic adjustments are key tolerance mechanisms observed in drought-resilient

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genotypes. At the reproductive stage, drought results in fewer siliques per plant, lower seeds per silique, reduced seed weight, and diminished seed oil content, severely constraining economic yield and quality (Ahmed et al., 2023; Rahman et al., 2023).

On the contrary, despite the significance of mustard and the prevalence of drought stress in Bangladesh, limited studies have comprehensively assessed morphophysiological, biochemical, seed quality, and yield responses across multiple mustard genotypes under controlled drought environments. Previous studies primarily focused on yield loss estimation or morphological assessment, lacking integrative evaluation that links drought tolerance mechanisms with physiological, biochemical, and yield parameters (Khatun et al., 2024; Ali, 2021). Furthermore, insufficient research exists addressing genotype-specific drought tolerance and stability indices under northern Bangladesh agro-ecological conditions, particularly in Bogura region. Therefore, identification of drought-tolerant, high-yielding mustard genotypes is essential for climate-resilient agriculture and sustainable edible oil production.

Considering the above scenario, the current lack of information regarding the impact of drought stress on mustard genotypes in North region of Bangladesh, this research aimed to evaluate the morpho-physiological, biochemical, and seed quality responses of mustard genotypes under drought stress and assess their effects on yield and yield components, and to identify drought-tolerant mustard genotypes suitable for Bangladesh and determine the relationship among key morpho-physiological, biochemical, seed quality traits, and yield performance.

2. MATERIALS AND METHODS

2.1 Experimental Site, Soil, and Climate

The present research was conducted at Shibganj upazila under Bogura district during 2023–2024 to evaluate drought stress impacts on mustard and identify drought-adaptive genotypes. Bogura District, located in the northern part of Bangladesh under the Rajshahi Division, lies approximately between 24°51'N latitude and 89°22'E longitude and features low-lying floodplain terrain. The region predominantly belongs to the Karatoya–Bangali Floodplain (AEZ-4) and partly to the Lower Atrai Basin (AEZ-5), characterized by fertile alluvial soils mainly grey silt loams, silty clay loams, and heavier clays in basin depressions. Bogura has a humid subtropical climate, marked by a hot, humid monsoon season and a cool, dry winter. Annual rainfall ranges from 1,400–1,600 mm, while temperatures vary from around 11–12°C in winter to 35°C or higher in summer (Alam et al., 2024).

2.2 Design and Experimental Layout

The present research was conducted at Shibganj upazila under Bogura district during 2023–2024 to evaluate drought stress impacts on mustard and identify drought-adaptive genotypes. Eight BARI Sarisha genotypes (BARI Sarisha-10, 11, 12, 13, 14, 15, 16, and 17) were tested under two moisture regimes well-watered and drought stress using a Randomized Complete Block Design (RCBD) with three replications, totaling 48 experimental plots. A unit plot was 2.0 m by 1.0 m in size. The distance between row to row and plant to plant was 40cm and 10cm, respectively.

2.3 Crop Husbandry

Land preparation typically begins on last week of October 2024, involving 4 cross ploughings followed by laddering to ensure a fine, firm, and weed-free seedbed suitable for small-sized mustard seeds. After ploughing, the recommended fertilizer dose generally consists of Urea 250–300 kg ha⁻¹, TSP 150–200 kg ha⁻¹, MOP 75–100 kg ha⁻¹, Gypsum 100–150 kg ha⁻¹, and Boron 3–5 kg ha⁻¹ depending on soil fertility status (FRG, 2012). Organic manure, especially farmyard manure at 5–10 t ha⁻¹, is often applied during final land preparation to improve soil structure and microbial activity. One-third of urea is applied as basal, and the remaining is top-dressed at 25–30 days after sowing (DAS). All tested genotypes (BARI Sarisha- 10, 11, 12, 13, 14, 15, 16, & 17 of mustard were sown on 1st November 2024 ensuring favorable cool temperatures and proper vegetative growth

before flowering. Seeds are sown in line sowing. It improves plant population, facilitates intercultural operations, and enhances sunlight penetration. Intercultural operations include thinning at 10–12 DAS to maintain optimum plant density, manual weeding or hoeing twice at 15–20 DAS and 30–35 DAS, and irrigation at the flowering and pod-filling stages under well-watered (control) plot. Besides, in case of drought condition, there is no irrigation in this plot. Pest and disease management is carried out by adopting integrated approaches including seed treatment with fungicide, timely weeding, biological agents, and chemical control when necessary. All genotypes of mustard are harvested 95 days after sowing, when siliques turn yellowish-brown, and seeds harden. Proper post-harvest drying ensures seed quality and storage stability.

2.4 Data Collection Procedure

Comprehensive agronomic, physiological, biochemical, and seed quality traits were measured, including plant height, primary branches, leaf area, chlorophyll content, proline accumulation, siliques plant⁻¹, seeds silique⁻¹, silique length, thousand-seed weight, seed yield, biological yield, harvest index, oil content, and protein content. Plant height (cm) was measured after harvesting of mustard and number of primary branches per plant was calculated at 60 days of sowing for each replication. Besides, number of effective siliques per plant, number of seed per silique, length of silique (cm) and weight of 1000 seed (g) were counted as well as measured after harvesting of crop, respectively. After weight of seed, it was converted into tone per hectare. Chlorophyll content (mg g⁻¹FW⁻¹) and proline content (μmol g⁻¹) were measured according to Arnon method and Bates et al, (1973) method, respectively.

2.5 Statistical Analysis

All of the data collected on various parameters was combined and organized for statistical purposes. The recorded data on various parameters were statistically following R statistics software package version 3.5.3. The treatment means were compared by Least Significant Difference (LSD) test at a 5% level of significance (Gomez and Gomez, 1984). Pearson's Correlation Coefficient was used to calculate the association between yield attributes and DSI under drought stress using R statistical software version 3.5.3.

3. RESULTS

3.1 Impact of Drought Stress and Genotypes on Morphophysiological Traits of Mustard

Drought stress had a significant influence on plant height and primary branch production in mustard genotypes, as indicated by the highly significant (**) and significant (*) effects for plant height and number of primary branches per plant, respectively (Table 1). Across treatments, plants grown under control conditions exhibited greater plant stature and branching compared to those subjected to drought stress. Among the genotypes, BARI Sarisha-16 recorded the highest plant height (182.63 cm) and number of primary branches (8.96) under control conditions, followed by BARI Sarisha-11. In contrast, BARI Sarisha-12 and BARI Sarisha-14 produced the shortest plants and fewer branches under both moisture regimes. Besides, under drought stress, plant height declined noticeably in all genotypes, with the reduction being most prominent in BARI Sarisha-11, BARI Sarisha-13, and BARI Sarisha-15, whereas BARI Sarisha-16 maintained relatively higher plant height (168.97 cm) and superior branching ability (8.34 branches/plant), demonstrating better tolerance to water deficit. Conversely, BARI Sarisha-10 showed the lowest primary branch number (4.65) under drought conditions, indicating greater susceptibility to moisture stress. The results clearly reveal that drought stress adversely affects vegetative growth traits in mustard, and the magnitude of reduction varies among genotypes. BARI Sarisha-16 emerged as the most resilient genotype with minimum reduction in plant height and branching, while BARI Sarisha-12, BARI Sarisha-14, and BARI Sarisha-10 were found to be more sensitive to water deficit conditions. The low coefficients of variation (6.85% for plant height and 5.12% for branches) further reflect the reliability of the experimental data.

Table 1: Impact of drought stress and genotypes on morphophysiological traits of mustard

Drought stress	Genotypes	Plant height (cm)	Primary Branch/plant (No.)
Control	BARI Sarisha-10	92.34de	5.23jk
	BARI Sarisha-11	122.42c	7.01c
	BARI Sarisha-12	72.14hi	6.02gh
	BARI Sarisha-13	93.15de	6.53e

Table 1 (Cont): Impact of drought stress and genotypes on morphophysiological traits of mustard

Drought stress	Genotypes	Plant height (cm)	Primary Branch/plant (No.)
Control	BARI Sarisha-14	78.96fg	5.54i
	BARI Sarisha-15	93.16de	6.34fg
	BARI Sarisha-16	182.63a	8.96a
	BARI Sarisha-17	90.38ef	6.42ef
Drought	BARI Sarisha-10	78.49fg	4.65k
	BARI Sarisha-11	100.02d	6.71d
	BARI Sarisha-12	62.48i	5.62h
	BARI Sarisha-13	73.65gh	6.44ef
	BARI Sarisha-14	65.48i	5.33j
	BARI Sarisha-15	73.69gh	6.12g
	BARI Sarisha-16	168.97b	8.34b
	BARI Sarisha-17	72.19hi	6.35fg
LS		**	*
CV (%)		6.85	5.12

In column, means followed by different letters are significantly different. *means at 5% level of probability, **means at 1% level of probability, LS means level of significant, and CV means co-efficiency of variance

3.2 Effect of Drought Stress and Genotypes on Biochemical Traits of Mustard

In Table 2, the biochemical responses of eight mustard genotypes to drought stress are clearly differentiated, showing significant effects on both chlorophyll content (mg g^{-1} FW) and proline accumulation ($\mu\text{mol g}^{-1}$ FW) at $p < 0.01$ for chlorophyll and $p < 0.05$ for proline. Under control conditions, BARI Sarisha-16 exhibited the highest chlorophyll (1.38 mg g^{-1} FW) and a moderate proline content ($0.33 \mu\text{mol g}^{-1}$). Under drought stress, this genotype maintained relatively higher chlorophyll (1.26 mg g^{-1}

FW) compared with other genotypes and showed the greatest increase in proline ($0.61 \mu\text{mol g}^{-1}$) among all genotypes. In contrast, BARI Sarisha-10 had the lowest chlorophyll both under control (0.83 mg g^{-1} FW) and drought (0.69 mg g^{-1} FW), and the lowest proline under stress ($0.29 \mu\text{mol g}^{-1}$). The drop in chlorophyll under drought for most genotypes indicates suppression of pigment synthesis or stability; simultaneously, the rise in proline under drought indicates activation of osmotic/biochemical stress response mechanisms. The coefficient of variation (CV) values, 6.28% for chlorophyll and 7.63% for proline, suggest acceptable experimental precision. Overall, the data show that drought stress significantly reduces chlorophyll content while elevating proline levels, and genotypes differ markedly in the magnitude of these responses.

Table 2: Effect of drought stress and genotypes on biochemical traits of mustard

Drought stress	Genotypes	Chlorophyll content ($\text{mg g}^{-1}\text{FW}^{-1}$)	Proline content ($\mu\text{mol g}^{-1}$)
Control	BARI Sarisha-10	0.83g	0.17k
	BARI Sarisha-11	1.24bc	0.29f
	BARI Sarisha-12	0.99ef	0.21i
	BARI Sarisha-13	1.19c	0.26g
	BARI Sarisha-14	0.92fg	0.19j
	BARI Sarisha-15	1.10e	0.23h
	BARI Sarisha-16	1.38a	0.33ef
	BARI Sarisha-17	1.14d	0.24h
Drought	BARI Sarisha-10	0.69i	0.29f
	BARI Sarisha-11	1.12e	0.54b
	BARI Sarisha-12	0.85g	0.35e
	BARI Sarisha-13	1.04ef	0.47c
	BARI Sarisha-14	0.73h	0.31ef
	BARI Sarisha-15	0.92fg	0.39de
	BARI Sarisha-16	1.26b	0.61a
	BARI Sarisha-17	0.96f	0.42d
LS		**	*
CV (%)		6.28	7.63

In column, means followed by different letters are significantly different. *means at 5% level of probability, **means at 1% level of probability, LS means level of significant, and CV means co-efficiency of variance

3.3 Seed Quality Response of Mustard Genotypes under Drought Stress

The data from Table 3 indicate that both genotype and drought stress had

significant effects on seed quality traits specifically, oil content (%) and protein content (%) in mustard. Under control conditions, BARI Sarisha-16 recorded the highest oil content (36.03%) and protein content (22.25%), while BARI Sarisha-10 recorded the lowest values (22.01% oil, 16.48% protein). Under drought conditions, oil and protein contents declined across all genotypes: for example, BARI Sarisha-16's oil content declined to 34.14% and protein to 21.57%. The smallest reductions were

observed in BARI Sarisha-16, whereas genotypes such as BARI Sarisha-10 and BARI Sarisha-14 showed larger declines (oil to 20.17% and 21.32%, respectively; protein to 15.55% and 16.29%). The coefficients of variation (CV)-4.89% for oil content and 6.97% for protein content suggest

acceptable experimental precision. Overall, the results highlight that drought stress diminishes seed quality traits, but genotypes differ markedly in their retention of oil and protein under stress.

Table 3: Seed quality response of mustard genotypes under drought stress

Drought stress	Genotypes	Oil content (%)	Protein content (%)
Control	BARI Sarisha-10	22.01h	16.48g
	BARI Sarisha-11	31.12c	20.63c
	BARI Sarisha-12	26.16f	18.66e
	BARI Sarisha-13	30.75cd	20.02c
	BARI Sarisha-14	23.09gh	17.48f
	BARI Sarisha-15	27.24ef	19.18d
	BARI Sarisha-16	36.03a	22.25a
Drought	BARI Sarisha-10	20.17i	15.55h
	BARI Sarisha-11	30.05cd	19.41d
	BARI Sarisha-12	24.08g	16.44g
	BARI Sarisha-13	28.14e	18.17e
	BARI Sarisha-14	21.32hi	16.29gh
	BARI Sarisha-15	25.10fg	17.29f
	BARI Sarisha-16	34.14b	21.57b
	BARI Sarisha-17	24.06g	18.04e
Level of sig.		*	**
CV (%)		4.89	6.97

In column, means followed by different letters are significantly different. *means at 5% level of probability, **means at 1% level of probability, LS means level of significant, and CV means co-efficiency of variance

3.4 Influence of Drought Stress and Genotypic Variation on Seed Yield and Yield Attributes of Mustard Crop

The results showed that drought stress significantly reduced seed yield and yield-attributing traits across all mustard genotypes (Table 4 and Figure 1 & 2). Under control conditions, BARI Sarisha-16 exhibited the highest effective siliques plant⁻¹ (170.21), 1000-seed weight (4.55 g), and seed yield (2.02 t ha⁻¹), followed by BARI Sarisha-11 and BARI Sarisha-13.

Under drought stress, all parameters declined, with BARI Sarisha-16 still performing best (seed yield 1.90 t ha⁻¹), indicating strong drought tolerance. The lowest performance was recorded in BARI Sarisha-10 under drought (53.46 siliques plant⁻¹, 0.73 t ha⁻¹ seed yield, HI 26.93%). Biological yield followed a similar trend, with a maximum of 5.38 t ha⁻¹ in BARI Sarisha-16 under control and 5.06 t ha⁻¹ under drought. Harvest index (HI) ranged from 30.38-38.20% under control and 26.93-37.26% under drought. Overall, BARI Sarisha-16, BARI Sarisha-11, and BARI Sarisha-13 were superior performers, whereas BARI Sarisha-10 and BARI Sarisha-14 were relatively sensitive to drought stress.

Table 4: Influence of drought stress and genotypic variation on seed yield and yield attributes of mustard crop

Drought stress	Genotypes	Effective Siliques plant ⁻¹ (No.)	1000-seed weight (g)	Seed yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	HI (%)
Control	BARI Sarisha-10	70.38ij	1.86l	0.86kl	2.83lm	30.38
	BARI Sarisha-11	135.34c	3.32c	1.70c	4.45c	37.54
	BARI Sarisha-12	80.56fg	2.42hi	1.03j	3.12j	33.01
	BARI Sarisha-13	90.15e	3.10de	1.50e	4.16e	37.54
	BARI Sarisha-14	75.14gh	2.13j	0.92jk	2.97kl	30.97
	BARI Sarisha-15	82.43f	2.85gh	1.25h	3.75h	33.33
	BARI Sarisha-16	170.21a	4.55a	2.02a	5.38a	38.20
Drought	BARI Sarisha-10	53.46k	1.71m	0.73m	2.71n	26.93
	BARI Sarisha-11	120.52d	3.26cd	1.61d	4.32d	37.26
	BARI Sarisha-12	69.45ij	2.36ij	0.95jk	3.04jk	31.25
	BARI Sarisha-13	80.14gh	3.04ef	1.43f	4.05f	35.30
	BARI Sarisha-14	63.49jk	2.06k	0.89kl	2.86lm	0.311
	BARI Sarisha-15	70.42ij	2.80gh	1.19i	3.34i	0.35
	BARI Sarisha-16	152.46b	4.42b	1.90b	5.06b	36.05
	BARI Sarisha-17	72.38hi	2.92fg	1.35gh	3.83g	35.24
LS		**	**	*	**	
CV (%)		6.74	5.47	6.37	4.89	

In column, means followed by different letters are significantly different. *means at 5% level of probability, **means at 1% level of probability,

***means at 0.1% level of probability, LS means level of significant, and CV means co-efficiency of variance

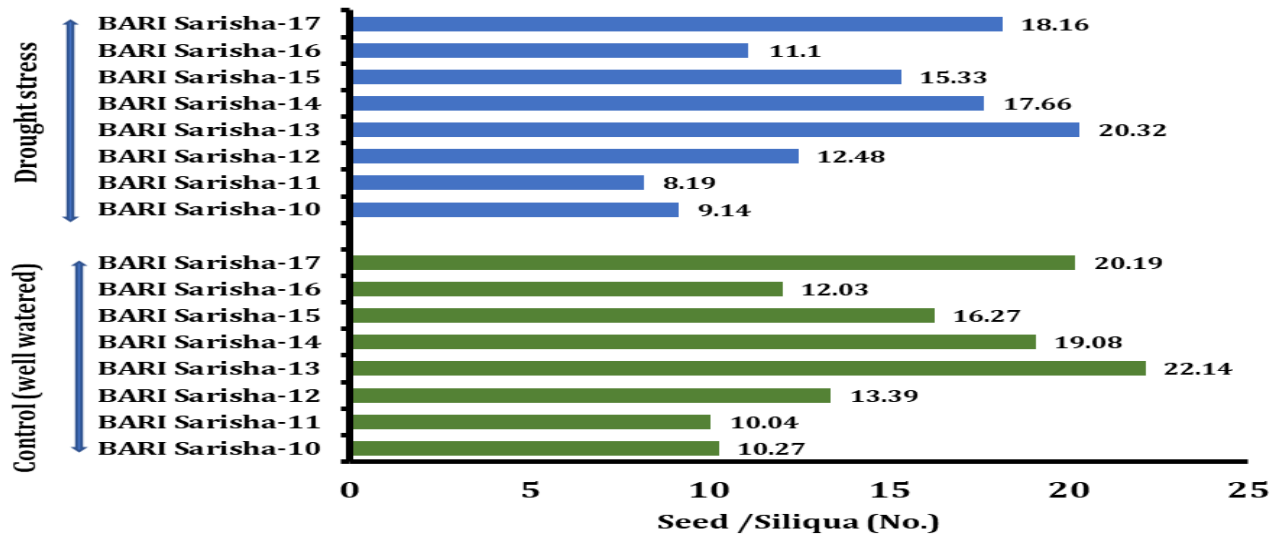


Figure 1: Influence of drought stress and genotypic variation on number of seed per siliqua of mustard crop

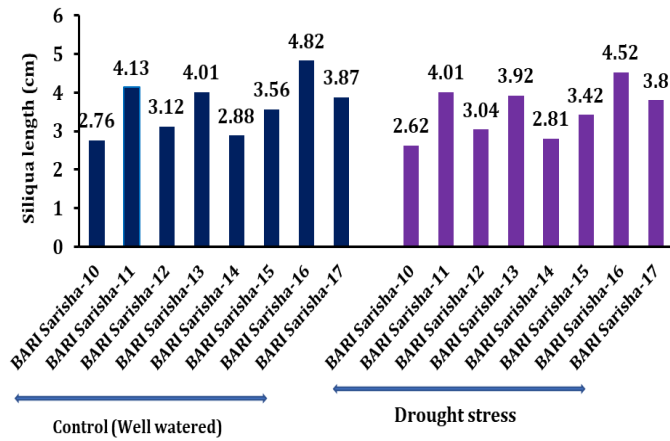


Figure 2: Influence of drought stress and genotypic variation on length of siliqua (cm) of mustard crop

3.5 Impact of Drought Stress and Genotypes on Yield Stability of Mustard

The Drought Susceptibility Index (DSI) indicated substantial variation in drought tolerance among the tested mustard genotypes (Figure 3). Genotypes with lower DSI values demonstrated greater yield stability under water-limited conditions, while higher DSI values reflected higher

yield reduction due to drought stress. Among all genotypes, BARI Sarisha-16 (0.55) exhibited the lowest DSI, confirming it as the most drought-tolerant and stable performer. It was closely followed by BARI Sarisha-11 (0.60), also showing high stability and strong drought resilience. Moderate drought tolerance was recorded in BARI Sarisha-13 (0.78), BARI Sarisha-15 (0.80), and BARI Sarisha-17 (0.88), indicating partial yield reduction under stress. BARI Sarisha-14 (1.00) showed intermediate susceptibility. In contrast, BARI Sarisha-12 (1.30) and particularly BARI Sarisha-10 (2.53) exhibited high drought susceptibility, with Sarisha-10 suffering the greatest proportional yield decline, indicating its unsuitability for drought-prone environments.

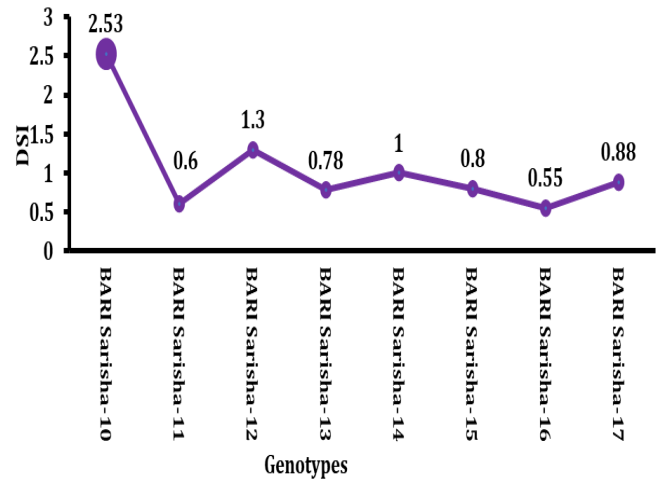


Figure 3: Impact of drought stress and genotypes on yield stability of mustard

3.6 Correlation (r) Between DSI for Yield and Yield Attributes of Mustard Crop under Drought Stress

Figure 4 presents Pearson correlation coefficients between the Drought Susceptibility Index (DSI) for seed yield and various morpho-physiological, biochemical, yield-component and quality traits in mustard under drought stress. Significant negative correlations with DSI were observed for key traits: plant height ($r = -0.402$), primary branches per plant ($r = -0.658^*$), chlorophyll content ($r = -0.811^*$), effective siliques per plant ($r = -0.560^{**}$), 1000-seed weight ($r = -0.722^{**}$), seed yield ($r = -0.721^{**}$), biological yield ($r = -0.718^*$) and oil content ($r = -0.742^*$). These negative correlations indicate that higher values of these traits are associated with lower DSI (i.e., greater yield stability under drought). On the other hand, seeds per siliqua (SDS) showed a weak negative or non-significant correlation ($r = -0.335^*$), suggesting less consistent influence on DSI. Overall, traits such as chlorophyll content, primary branching, effective siliques, 1000-seed weight, and oil content appear to be strong indicators of yield stability under drought in mustard.

Table 5: Correlation (r) between DSI for yield and yield attributes of mustard crop under drought stress

	PH	PBP	Chlo C	PC	ESP	SDS	SL	TSWt	ESY	BY	HI	OC	PRC	DSI
PH	1													
PBP	0.878***	1												
Chlo C	0.778***	0.915	1											
PC	0.317	0.479*	0.278	1										
ESP	0.935***	0.933*	0.872*	0.4191	1									

Table 5 (Cont): Correlation (r) between DSI for yield and yield attributes of mustard crop under drought stress

	PH	PBP	Chlo C	PC	ESP	SDS	SL	TSWt	ESY	BY	HI	OC	PRC	DSI
SDS	-0.369	-0.103	0.014**	-0.2179	-0.356	1								
SL	0.763***	0.945*	0.937**	0.5281*	0.857**	0.0158*	1							
TSWt	0.843***	0.988**	0.911***	0.5672*	0.907***	-0.0768**	0.9704***	1						
ESY	0.808***	0.956***	0.940***	0.5381*	0.907***	-0.0692**	0.9917***	0.975**	1					
BY	0.834***	0.960***	0.940**	0.5228**	0.908**	-0.0657**	0.9900*	0.978*	0.994**	1				
HI	0.409	0.421*	0.592*	0.0548	0.462*	-0.1045*	0.4911*	0.412**	0.475*	0.514**	1			
OC	0.820***	0.946***	0.974*	0.4070*	0.912*	-0.0672*	0.9508**	0.951*	0.960**	0.961*	0.525	1		
PRC	0.832	0.938**	0.983*	0.3016*	0.909*	-0.0395**	0.9265	0.926**	0.940*	0.942*	0.551*	0.970**	1	
DSI	-0.402	-0.658*	-0.811*	-0.7583	-0.563**	-0.3355*	-0.7382*	-0.722**	-0.721**	-0.718*	-0.737*	-0.742*	-0.805*	1

Here, PH=Plant height (cm), PBP=Primary Branches plant⁻¹ (No.), LAI=Leaf area index, Chlo C=Chlorophyll content (mg g⁻¹FW-1), PC=Proline content (μmol g⁻¹), ESP=Effective Siliques plant⁻¹ (No.), SDS=Seeds silique⁻¹(No.), SL= Siliqua length (cm), TSWt= 1000-seed weight (g), ESY= Effective Seed yield (t ha⁻¹), BY=Biological yield (t ha⁻¹), HI=Harvest Index (%), OC= Oil content (%) and PRC= Protein content (%). *, ** & *** means 5, 1 & 0.1% level of probability.

4. DISCUSSIONS

4.1 Impact of Drought Stress and Genotypes on Morphophysiological Traits of Mustard

In case of morphological trait influenced by variety and drought stress, the data in Table 1 show that both drought stress and genotype significantly influenced morphophysiological traits in mustard, namely plant height and primary branches per plant. The significant reduction in plant height under drought across all genotypes aligns with earlier findings in Brassica juncea that moisture deficiency impairs vegetative growth (Rani et al., 2024). Among the genotypes evaluated, BARI Sarisha-16 maintained the highest plant height (182.63 cm in control; 168.97 cm under drought) and the highest number of primary branches, indicating its superior adaptability and tolerance to water limitation. This differential performance suggests inherent genetic variation in drought response among mustard genotypes, which has also been documented by where some genotypes of Indian mustard exhibited smaller yield reductions under rain-fed vs irrigated conditions (Sandhu et al., 2022). The greater resilience of BARI Sarisha-16 may be attributed to better maintenance of growth under stress, possibly by retaining higher leaf area or root water uptake efficiency, factors often associated with drought-tolerance in oilseed Brassicas (Chowdhury 2016).

In contrast, genotypes such as BARI Sarisha-12 and BARI Sarisha-14 exhibited the lowest heights and branching under both control and drought conditions (72.14 cm and 78.96 cm, respectively, in control; 62.48 cm and 65.48 cm under drought), identifying them as more drought-sensitive. The low branching under stress in these genotypes further reflects the typical reduction in sink capacity under water limitation, which can reduce assimilate partitioning to developing organs (Rani et al., 2024). The reduction in branching from control to drought was less severe in tolerant genotypes (e.g., BARI Sarisha-16: from 8.96 to 8.34) than in sensitive ones (e.g., BARI Sarisha-10: from 5.23 to 4.65), indicating that maintenance of branching may be a useful selection criterion for drought tolerance. Prior research has demonstrated that the number of branches per plant can strongly influence eventual seed yield and is sensitive to environmental stress (Ali, 2021). Moreover, the coefficient of variation (CV) values (6.85% for plant height, 5.12% for branches) indicate moderate variability among treatments and genotypes, supporting the robustness of detected differences. In summary, the results highlight that drought stress reduces morphophysiological growth in mustard, but the extent of reduction varies substantially among genotypes. BARI Sarisha-16 emerges as a promising genotype for drought-prone environments in Bangladesh due to its superior performance under both control and stress conditions. Future work should explore the physiological and root traits that underlie this tolerance to better inform breeding for drought-resilient mustard cultivars.

4.2 Effect of Drought Stress and Genotypes on Biochemical Traits of Mustard

Drought stress significantly reduced chlorophyll content while markedly increasing proline accumulation across mustard genotypes, indicating physiological adjustments to water deficit (Table 2) BARI Sarisha-16

consistently maintained the highest chlorophyll level under both control and drought conditions, demonstrating stronger tolerance, whereas BARI Sarisha-10 showed the lowest values, reflecting higher sensitivity. The enhanced proline concentration under drought, particularly in BARI Sarisha-16, suggests osmotic adjustment and protective roles against oxidative stress. Similar trends were reported in mustard where drought-induced decreases in chlorophyll and increases in proline were associated with improved stress resilience (Rahman et al., 2023; Islam et al., 2022). Higher proline synthesis helps stabilize membranes, proteins, and cellular functions, contributing to drought adaptation (Khatun et al., 2024). Thus, genotype-dependent biochemical responses highlight the potential of BARI Sarisha-16 and BARI Sarisha-11 for cultivation in water-limited environments.

4.3 Seed Quality Response of Mustard Genotypes under Drought Stress

Drought stress significantly compromised seed quality in mustard genotypes, reflecting the well-documented sensitivity of oil- and protein-accumulating metabolic pathways to moisture deficit (Table 3). Genotype BARI Sarisha-16 maintained the highest oil (34.14%) and protein (21.57%) under drought, suggesting robust physiological and metabolic resilience. In contrast, genotypes such as BARI Sarisha-10 and BARI Sarisha-14 exhibited more pronounced reductions, underscoring differential genetic tolerance to water limitation. Similar patterns have been reported in oilseed Brassicas where drought reduces oil concentration and protein synthesis by limiting carbon assimilation and nitrogen fixation (Sharma et al., 2022; Rani et al., 2024; Limbalkar et al., 2023). Hence, selecting genotypes with minimal reduction in seed quality under drought is vital for breeding climate-resilient mustard cultivars in Bangladesh.

4.4 Influence of Drought Stress and Genotypic Variation on Seed Yield and Yield Attributes of Mustard Crop

Drought stress markedly reduced seed yield and yield-related traits across mustard genotypes, reflecting the sensitivity of Brassica crops to water deficit. Effective siliques plant⁻¹, seeds silique⁻¹, siliqua length, 1000-seed weight, and seed yield all declined significantly under drought stress. Among the genotypes, BARI Sarisha-16 consistently showed superior performance, maintaining the highest siliques plant⁻¹ (152.46), siliqua length (4.52 cm), and seed yield (1.90 t ha⁻¹) under drought, compared to BARI Sarisha-10, which showed the lowest values (53.46 siliques plant⁻¹; 0.73 t ha⁻¹ yield) (Table 4 and Figure 1 and 2). This demonstrates strong genotypic variation in drought tolerance, in line with the findings that drought stress limits assimilate formation and pod development in mustard (Hossain et al., 2021). Besides, the reduction in seed yield under drought was more pronounced in sensitive genotypes (e.g., BARI Sarisha-10, BARI Sarisha-14), which exhibited substantial declines in siliqua formation and seed fill. Drought-induced reduction in siliques and seed size is commonly attributed to impaired photosynthetic efficiency, reduced source-sink activity, and oxidative stress that disrupt reproductive processes (Rahman et al., 2022; Sharma and Singh 2020). The relatively stable 1000-seed weight in BARI Sarisha-16 (4.42 g under drought vs. 4.55 g control) suggests better maintenance of carbon allocation to seeds, supporting previous reports that drought-tolerant mustard lines maintain higher seed weight under water-limited conditions (Khatun et al., 2023).

Harvest index (HI) also declined slightly under drought, with the highest value recorded in BARI Sarisha-11 (37.26%) and the lowest in BARI Sarisha-10 (26.93%) under stress. Reduced HI under drought has been associated with restricted biomass accumulation and reduced

translocation efficiency to reproductive parts (Islam et al., 2019). BARI Sarisha-16, however, maintained a comparatively higher biological yield and HI under drought, highlighting its strong adaptive capacity and resource efficiency, consistent with reports emphasizing genotype-specific drought resilience in Brassica juncea (Zhang et al., 2022). Overall, genotypes such as BARI Sarisha-16 and BARI Sarisha-11 demonstrated superior drought tolerance by sustaining higher pod set, seed number, seed weight, and yield efficiency. These results confirm that maintaining siliqua traits and seed weight are crucial indicators of drought tolerance in mustard, and such genotypes can be prioritized in breeding programs for water-limited ecosystems in Bangladesh.

4.5 Impact of Drought Stress and Genotypes on Yield Stability of Mustard

Under drought conditions, notable variation in drought susceptibility index (DSI) among mustard genotypes highlights distinct levels of yield stability (Figure 3). BARI Sarisha-16 (DSI = 0.55) and BARI Sarisha-11 (0.60) showed the greatest tolerance, indicating strong adaptive capacity and minimal yield reduction under water stress. Moderate stability was observed in BARI Sarisha-13 (0.78), BARI Sarisha-15 (0.80), and BARI Sarisha-17 (0.88), suggesting partial drought resilience. In contrast, BARI Sarisha-10 exhibited extreme susceptibility (2.53), followed by BARI Sarisha-12 (1.30) and BARI Sarisha-14 (1.00), reflecting poor drought adaptability. Lower DSI values are associated with efficient physiological adjustment, osmotic regulation, and sustained assimilate allocation under stress (Sharma and Singh 2020; Rahman et al., 2022). Similar studies in Brassica juncea confirm that drought-tolerant genotypes maintain higher yield stability through superior resource-use efficiency and stress-tolerant biochemical pathways (Khatun et al., 2023). Accordingly, BARI Sarisha-16 and BARI Sarisha-11 emerge as promising climate-resilient candidates for water-limited environments.

4.6 Correlation (r) Between DSI for Yield and Yield Attributes of Mustard Crop under Drought Stress

The significant negative correlations between DSI and traits like chlorophyll content ($r = -0.811$), primary branches ($r = -0.658$), effective siliques ($r = -0.560$) and 1000-seed weight ($r = -0.722$) emphasize their importance in maintaining yield stability under drought (Figure 4). These results are consistent with recent findings that physiological stability (e.g., retained chlorophyll) and strong reproductive component (siliques/plant, seed weight) underpin drought resilience in Brassica crops (Sharma et al. 2022; Zamani, 2025). Furthermore, the strong negative correlation with oil content ($r = -0.742$) suggests genotypes capable of retaining high oil under stress also show better yield stability—a link also reported by Raina (2023) in *B. juncea*. Traits with weaker correlation (e.g., seeds per silique) appear less reliable as indirect selection criteria. Thus, for breeding drought-tolerant mustard, focusing on chlorophyll retention, branching capacity, siliques per plant and seed weight may enhance selection efficiency for stable yield in water-limited environments.

5. CONCLUSION

This study clearly demonstrates that drought stress substantially impairs the growth, physiological performance, and productivity of mustard, highlighting considerable genotypic variation in stress tolerance. Across evaluated traits, drought caused significant reductions in chlorophyll content, siliques per plant, seed size, and overall seed yield, while inducing notable increases in proline accumulation as an adaptive response. Among the tested genotypes, BARI Sarisha-16 consistently exhibited superior performance under water-limited conditions, reflected in higher photosynthetic pigment retention, greater reproductive success, enhanced seed yield, and the lowest drought susceptibility index, followed by BARI Sarisha-11 and BARI Sarisha-13. Conversely, BARI Sarisha-10 and BARI Sarisha-12 were identified as highly drought-sensitive. These findings suggest that BARI Sarisha-16 is a promising genotype for cultivation in drought-prone environments and serves as a strong candidate for breeding programs aimed at improving drought resilience and ensuring sustainable mustard production under changing climate scenarios.

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