ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2805-5063 (Online)
CODEN: PPSCCU

Plant Physiology and Soil Chemistry (PPSC)

DOI: http://doi.org/10.26480/ppsc.02.2025.105.111

RESEARCH ARTICLE

MORPHO-PHYSIOLOGICAL AND BIOCHEMICAL RESPONSES OF SORGHUM GERMPLASM TO SALINITY STRESS UNDER POT CULTURE

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ARTICLE DETAILS

Article History:

Received 24 May 2025
Revised 28 June 2025
Accepted 12 Junel 2025
Available online 31 July 2025

ABSTRACT

An experiment was conducted in the Plant Physiology Laboratory and Glasshouse of the Department of Crop Botany, Bangladesh Agricultural University, Mymensingh during 2016-17. The trial was laid out in two factorial designs with three replications using ten Sorghum germplasm (eight tolerant and two susceptible), previously identified in an earlier study. The plants were grown under control and saline (12 dS m^{-1}) conditions to investigate the morpho-physiological and bio-chemical mechanisms underlying salt tolerance in Sorghum at the reproductive stage. The morpho-physiological and biochemical traits of the Sorghum germplasm varied significantly under salinity stress in pot culture. Parameters such as plant height at different stages, SPAD value, root length, root, shoot, and total dry weight, days to panicle initiation, and proline content at both vegetative and reproductive stages were recorded. Salinity stress resulted in a marked increase in root and stem Na^+ content. The total Na^+/K^+ and Na^+/Ca^{2+} ratios were significantly higher in the susceptible germplasm compared to the tolerant ones. Among the tested lines, Hybrid Sorgo, Sorghum BD-701, Sorghum BD-730, Sorghum BD-731, Sorghum BD-733, and Sorghum BD-737 showed superior performance under saline conditions. Notably, Sorghum BD-737 produced the highest grain yield, followed by Hybrid Sorgo. Based on these results, Sorghum BD-737, Hybrid Sorgo, Sorghum BD-701, and Sorghum BD-730 are recommended for further field trials in different coastal regions of Bangladesh.

KEYWORDS

Sorghum, Salinity stress, morpho-physiological and Biochemical traits

1. INTRODUCTION

Soil salinity, marked by excessive accumulation of soluble salts particularly sodium chloride in the root zone, poses a severe threat to agricultural productivity worldwide (FAO, 2021). When soil electrical conductivity (EC) surpasses 4 dS m^{-1} and the exchangeable sodium percentage (ESP) exceeds 15%, plant growth is significantly hindered due to impaired water uptake, ionic toxicity, and oxidative damage (Munns and Tester, 2008; Gupta and Huang, 2014). Alarmingly, more than 20% of global irrigated and arable lands are already affected by salinity, with projections indicating further expansion due to unsustainable irrigation practices, rising sea levels, and climate change-induced weather extremes (Wicke et al., 2011; Shahid et al., 2018). Coastal regions in South Asia, where saltwater intrusion has intensified, face particularly dire consequences, jeopardizing food security for nearly 600 million inhabitants (Wheeler and von Braun, 2013). Among the most vulnerable nations, Bangladesh contends with salinity encroachment across approximately 1.05 million hectares of cultivable land, predominantly in 19 coastal districts that constitute nearly one-third of the country's landmass (SRDI, 2010; Alam et al., 2017). Historical data reveal a troubling 26% increase in soil salinity over recent decades, driven by anthropogenic factors, recurrent tidal flooding, and reduced freshwater flow due to upstream water diversion (Mahmuduzzaman et al., 2014; Rahman et al., 2018). This escalating salinity crisis has drastically narrowed cropping options and diminished yields, particularly during the dry season when freshwater supplies are most limited (Haque, 2006; Miah et al., 2004). In response, the cultivation of salt-tolerant crop varieties has emerged as a vital adaptation strategy for sustaining agricultural output in affected regions.

Sorghum (*Sorghum bicolor* L. Moench), ranking as the fifth most crucial cereal crop globally, demonstrates exceptional tolerance to abiotic stresses, including salinity, drought, and high temperatures (Rakshit et al., 2014). With documented resilience to EC levels as high as 18 dS m^{-1}, sorghum presents a viable option for cultivation in salt-affected marginal lands (Mansour et al., 2021; Saberi and Aishah, 2013). Beyond its traditional role as a food and fodder source, this versatile crop holds increasing importance for bio-industrial applications, including biofuel production and sustainable material development (Rutto et al., 2013). The plant's adaptive mechanisms such as osmotic regulation, selective ion exclusion, proline accumulation, and enhanced antioxidant activity contribute to its remarkable stress tolerance (Kausar et al., 2012; Parida and Das, 2005; James et al., 2011). Despite these advantages, sorghum cultivation remains negligible in Bangladesh, with current production covering only 187 hectares and yielding a modest 254 tons annually (FAOSTAT, 2014). Existing research on sorghum's salinity tolerance has primarily employed hydroponic and controlled soil-based systems, revealing significant genetic variation in stress response traits (Yadav et al., 2021; Boutraa et al., 2010). Studies have identified several reliable physiological indicators of salt tolerance, including chlorophyll stability, relative water content (RWC), membrane integrity, and the activity of antioxidant enzymes like superoxide dismutase (SOD) and catalase (CAT) (Ashraf and Foolad, 2007; Ahmad et al., 2015;Mbarki et al., 2018). However, these investigations have largely been conducted in non-Bangladeshi environments and typically examined limited genetic material under single stress levels, leaving critical knowledge gaps

Quick Response Code	Access this article online	
	Website: www.ppsc.org.my	**DOI:** 10.26480/ppsc.02.2025.105.111

Cite The Article: Md. Eakramul Haque, Md. Rishad Abdullah, A.K.M. Golam Sarwar, Md.Akhter-Ul-Alam, Md. Al-Amin Hossain Talukder, Biplob Kumar Saha, A.K.M. Zakir Hossain (2025). Morpho-Physiological and Biochemical Responses of Sorghum Germplasm to Salinity Stress Under Pot Culture. *Plant Physiology and Soil Chemistry, 5(1): 105-111.*

regarding local adaptation.

Salinity tolerance research faces inherent challenges, including spatial and temporal variability in salt stress, complex genotype-environment interactions, and the dual osmotic-ionic nature of salinity stress (Munns and Tester, 2008). Traditional field-based evaluation methods are often compromised by environmental heterogeneity, underscoring the need for controlled experimental systems that enable precise stress imposition and response measurement. The current study addresses these methodological limitations through a carefully designed pot-culture experiment that facilitates accurate assessment of morpho-physiological and biochemical responses under regulated salinity conditions. This investigation holds particular significance for developing climate-resilient agricultural systems in Bangladesh's salinity-affected coastal zones. By systematically evaluating sorghum germplasm through an integrated analysis of agronomic performance and stress-responsive traits, the study aims to identify promising genotypes for saline agriculture while establishing a robust phenotyping framework for future breeding initiatives. Furthermore, this work represents one of the first comprehensive assessments of sorghum's salinity adaptation mechanisms in the South Asian context, offering valuable insights for sustainable crop production in salt-affected environments.

2. Materials and Methods

2.1 Experimental Site, time, and Climatic Conditions

A pot culture experiment was conducted at the net house of the Department of Crop Botany, Bangladesh Agricultural University (BAU), Mymensingh (24.75°N latitude, 90.50°E longitude) during the period from November 2016 to February 2017. The region is characterized by a subtropical monsoon climate with a dry winter.

2.2 Soil Collection and Preparation

The soil used in this experiment was collected from the cultivated field of BAU Farm, classified as non-calcareous Dark Grey Floodplain soil belonging to the Old Brahmaputra Floodplain (AEZ 9) with loamy texture (FAO, 2021). The collected soil was air-dried, ground gently, and passed through a 2 mm sieve to remove debris, visible pests, and plant residues. Prior to pot filling, the physical and chemical properties of the soil, including pH, electrical conductivity (EC), organic matter content, and available nutrients (N, P, K, S), were determined following standard procedures (Page et al., 1982).

2.3 Pot Preparation and Fertilization

A total of 60 perforated plastic pots (23 cm top diameter, 17 cm bottom diameter, 25 cm height) were used. Each pot was filled with 7.8 kg of prepared soil. Basal doses of fertilizers were applied at the rate of 4.25 g urea, 13.0 g triple super phosphate (TSP), and 7.31 g muriate of potash (MOP) per pot, mixed thoroughly with the soil prior to sowing, following the fertilizer recommendation guide of (BARC, 2012).

2.4 Plant Materials and Experimental Design

Ten Sorghum germplasm (Hybrid Sorgo, Sorghum BD-701, Sorghum BD-703, Sorghum BD-706, Sorghum BD-713, Sorghum BD-720, Sorghum BD-730, Sorghum BD-731, Sorghum BD-733 and Sorghum BD-737) were selected from previous hydroponic experiment along with two known salt-sensitive genotypes as checks. The experiment was arranged in a two-factorial Completely Randomized Design (CRD) with three replications. Factor A comprised ten Sorghum germplasm, while Factor B consisted of two salinity levels: Control (no added salt) and Salt stress (EC 12 dS m^{-1}).

2.5 Salinity Stress Imposition

Pre-germinated seeds (four to five) were sown directly into each pot and later thinned to maintain three uniform seedlings per pot at 14 days after sowing (DAS). Salinity treatment (12 dS m^{-1}) was imposed at 35 DAS using laboratory-grade NaCl, calculated to achieve the target EC level as measured by a calibrated EC meter (Hanna Instruments). A total of 65.07 g NaCl per pot was applied in four equal installments: the first in solution form, and the remaining alternately in crystal and solution form, avoiding direct contact with plant bases. Soil moisture was maintained daily by weighing each pot and replenishing the water lost (approximately 100 mL/day). Non-saline control pots received the same volume of distilled water without NaCl. EC levels of the saline treatments were regularly monitored to ensure consistency throughout the experiment.

2.6 Intercultural Operations

Routine intercultural operations, including hand-weeding, pest management, and light soil loosening, were carried out uniformly for the development of plant in all treatments. The pots were sheltered under a transparent polyethylene shed to prevent rainfall interference and to maintain uniform microclimatic conditions.

2.7 Data Collection of Morpho-physiological Traits

Plants were sampled at 60, 75, and 100 days after sowing (DAS) for morphological assessments. Plant height was measured from the soil surface to the tip of the longest leaf using a graduated scale (cm) prior to harvest. For root dry weight determination, roots were gently washed under running tap water, rinsed with distilled water, and oven-dried at 70 ± 2°C until a constant weight was achieved (g $hill^{-1}$). Shoot dry weight was obtained by separating leaf, stem, and panicle components, followed by oven-drying at 70 ± 2°C to constant weight (g $hill^{-1}$). Total dry matter (TDM) was calculated as the sum of root and shoot dry weights per hill. Yield-related parameters, including the number of effective tillers $hill^{-1}$, filled and unfilled grains $panicle^{-1}$, 1000-grain weight (g), and grain yield $hill^{-1}$ (g), were recorded at physiological maturity. The relative yield reduction under salinity stress, compared to the control, was calculated following the formula described by (Munns and Tester, 2008).

2.8 Biochemical Analysis

Proline content was quantified from the fourth fully expanded leaf at 70 DAS and the flag leaf at 90 DAS using the acid-ninhydrin method (Bates et al., 1973). Fresh leaf samples were transported to the laboratory in an icebox for immediate analysis. For ion analysis (Na^+, K^+, Ca^{2+}, Mg^{2+}), root, stem, and leaf tissues were harvested separately at 100 DAS, washed, oven-dried at 70 ± 2°C, and ground using a Wiley mill to pass through a 40-mesh sieve. The ground samples were digested with concentrated H_2SO_4 and H_2O_2 (Thomas et al., 1967). Sodium (Na^+) and potassium (K^+) contents were determined using a flame photometer (Model PFP7, Jenway) following Jackson (1973), and the K^+/Na^+ ratio was subsequently calculated. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were measured via atomic absorption spectrophotometry (AAS; Model AA-7000, Shimadzu) as per Isaac and Kerber (1971), with prior dilution in a 3.25% lanthanum chloride ($LaCl_3$) solution.

2.9 Statistical Analysis

Data were subjected to two-way ANOVA under Completely Randomized Design (CRD) using Statistix 10 software (Analytical Software, USA). Mean differences were evaluated by Tukey's Honest Significant Difference (HSD) test at a 5% significance level (Gomez and Gomez, 1984). Correlation analysis among physiological and yield parameters was also performed to determine associations under salinity stress.

3. Results and Discussion

3.1 Morphological Adaptations under Salinity Stress

The two-way ANOVA (Table 1) indicated that both genotype (G) and salinity treatment (S) significantly influenced key morphological traits, with notable G×S interactions for leaf number and plant height at various developmental stages ($p < 0.01$). Salt stress induced a pronounced reduction in leaf production, with the relative leaf number decreasing to 18% of control at 60 DAS and recovering moderately to 79% by 100 DAS. Similarly, plant height was curtailed to 11% of control by 60 DAS, improving to 71% at 100 DAS. These observations corroborate previous reports that salinity impairs cell division and elongation due to osmotic pressure and ion toxicity (Munns and Tester, 2008; Negrão et al., 2017). Genotype-specific analyses (Table 2) revealed that BD-737, BD-730, and BD-731 maintained the highest leaf number and stature under saline conditions, retaining >90% of their control height at 60 DAS and >75% leaf number at 100 DAS. In contrast, BD-703 and BD-733 exhibited substantial reductions (>25% decline) in these parameters, indicating inferior osmotic adjustment and growth vigor (Roy et al., 2014).

Table 1: Analysis of Variance (ANOVA) for various traits of ten Sorghum germplasm grown in pot under control and salt stress.

Parameters	Sources of variation			Relative value (Stress/Control)		
	Germplasm (G)	Salt stress (S)	GxS	RV (C)	LSD	CV
Number of leaves at 60 DAS				0.18	12.95	7.92

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Table 1: Analysis of Variance (ANOVA) for various traits of ten Sorghum germplasm grown in pot under control and salt stress.

Parameters	Sources of variation			Relative value (Stress/Control)		
	Germplasm (G)	Salt stress (S)	GxS	RV (C)	LSD	CV
Number of leaves at 75 DAS	0.20	0.05	0.84	0.85	23.01	14.08
No. of leaves at 100 DAS	0	0	0.82	0.79	30.83	24.92
Plant height at 60 DAS	0	0.01	0.54	0.11	17.11	11.14
Plant height at 75 DAS	0	0	0.10	0.53	26.64	17.44
SPAD at 75 DAS	0.01	0	0.28	0.07	14.75	9.73
Plant height at 100 DAS	0.03	0	0.81	0.71	45.96	35.63
Days to panicle initiation	0	0.01	0.03	0.02	5.34	3.06
Days to anthesis	0	0.50	0	0	9.11	5.33
Panicle length	0.08	0	0.28	0.54	55.39	59.12
Flag leaf length	0.12	0	0.05	0.06	38.87	27.67
Root length (cm)	0	0	0	0	10.42	9.20
Root dry weight at 100 DAS	0	0	0	0.04	77.85	110.03
Stem dry weight at 100 DAS	0	0	0	0	13.80	14.40
Leaf dry weight at 100 DAS	0	0	0	0	4.02	3.27
Total dry weight at 100 DAS	0	0	0	0	14.44	16.37
Proline in vegetative stage	0	0	0	0	11.47	4.13
Proline in reproductive stage	0	0	0	0	18.07	4.06
Root Na^+ at 100 DAS	0	0.14	0	0.28	733.09	180.27
Stem Na^+ at 100 DAS	0	0	0	0	578.19	23.19
Leaf Na^+ at 100 DAS	0	0	0	0	103.79	7.35
Root K^+ at 100 DAS	0	0	0	0.01	37.23	128.53
Stem K^+ at 100 DAS	0	0	0	0	9.84	11.28
Leaf K^+ at 100 DAS	0	0	0	0	3.42	3.09
Total Na^+ at 100 DAS	0	0	0	0	353.25	31.37
Total K^+ at 100 DAS	0	0.07	0	0	39.63	21.73
K^+-Na^+ ratio at 100 DAS	0	0	0	0	5.17	14.32
Total Ca^{++} at 100 DAS	0	0	0	0	10.60	6.48
Total Mg^{++} at 100 DAS	0	0	0	0	15.51	14.14
Na^+-Ca^{++} ratio at 100 DAS	0	0	0	0	338.48	19.18
Na^+-Mg^{++} ratio at 100 DAS	0	0	0	0	264.66	15.07

Table 2: Index of number of leaves, SPAD and plant height of ten Sorghum germplasm at different days after sowing under control and salinity conditions in pot culture.

Germplasm	Index of dry weight of stressed plant over control						
	Plant height at			Number of leaves			SPAD at 75 DAS
	60 DAS	75 DAS	100 DAS	60 DAS	75 DAS	100 DAS	
Hybrid Sorgo	91.26^{abc}	82.93^{a}	76.04^{a}	99.38^{a}	98.04^{a}	80.65^{a}	90.21^{ab}
Sorghum BD-701	86.73^{abc}	99.39^{a}	77.55^{a}	88.91^{ab}	82.78^{a}	59.87^{a}	90.145^{ab}
Sorghum BD-703	79.09^{c}	78.20^{a}	59.98^{a}	84.26^{b}	90.41^{a}	83.41^{a}	80.75^{b}
Sorghum BD-706	94.69^{abc}	90.08^{a}	86.48^{a}	97.09^{ab}	98.84^{a}	66.85^{a}	80.16^{b}
Sorghum BD-713	89.48^{abc}	94.70^{a}	82.15^{a}	92.89^{ab}	100.0^{a}	64.72^{a}	81.14^{b}
Sorghum BD-720	78.49^{c}	82.11^{a}	84.39^{a}	99.06^{a}	98.23^{a}	80.57^{a}	93.17^{ab}
Sorghum BD-730	97.98^{a}	90.60^{a}	80.82^{a}	91.84^{ab}	98.33^{a}	67.53^{a}	98.97^{a}
Sorghum BD-731	80.37^{bc}	98.05^{a}	54.61^{a}	100.23^{a}	100.0^{a}	75.20^{a}	92.58^{ab}
Sorghum BD-733	96.87^{ab}	76.24^{a}	58.52^{a}	100.11^{a}	92.69^{a}	67.16^{a}	79.41^{b}
Sorghum BD-737	100.01^{a}	97.95^{a}	91.40^{a}	99.62^{a}	93.06^{a}	75.19^{a}	96.95^{a}
LSD	17.108	26.64	45.964	12.951	23.007	30.83	14.749
CV (%)	11.14	17.44	35.63	7.92	14.08	24.92	9.73

Mean values bearing the dissimilar letter within the column differ significantly and having similar do not differ significantly

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3.2 Phenological Responses

Although days to panicle initiation remained largely unaffected, days to anthesis were significantly delayed in BD-737 (115% of control) and BD-731 (105% of control) under salt stress (Table 3). Flowering delay is a recognized adaptive strategy that allows plants to mitigate ionic stress during reproductive stages by prolonging vegetative growth and resource accumulation (Hernández et al., 2000; Farooq et al., 2009).

3.3 Reproductive Morphology and Root Architecture

Panicle length and flag leaf length indices varied considerably among genotypes (Table 3). BD-713 sustained 90.6% of its panicle length under stress, whereas BD-703 was reduced to 32%. Maintenance of reproductive organ dimensions is critical for yield stability under saline conditions (Flowers et al., 2015). Root length, a determinant of soil resource exploration, was best preserved in BD-701 and Hybrid Sorgo (>107%), highlighting genotypes with superior root plasticity (Läuchli and Grattan, 2007).

Table 3: Index of days to anthesis, panicle length, length of flag leaf, root length of ten Sorghum germplasm grown at control and salinity conditions in pot

Germplasm	Index of different traits of stressed plant over control			
	Days to anthesis	Panicle length	Flag leaf length	Root length
Hybrid Sorgo	98.48^{bcde}	59.32^{ab}	88.36^{a}	107.20^{a}
Sorghum BD-701	90.80^{e}	70.61^{ab}	105.33^{a}	111.13^{a}
Sorghum BD-703	95.04^{de}	32.08^{b}	77.31^{ab}	28.65^{e}
Sorghum BD-706	97.19^{bcde}	47.04^{ab}	90.97^{a}	66.67^{bc}
Sorghum BD-713	101.45^{bcd}	90.58^{a}	99.41^{a}	54.76^{d}
Sorghum BD-720	96.22^{cde}	57.0^{ab}	83.80^{ab}	50.65^{d}
Sorghum BD-730	92.55^{de}	55.70^{ab}	96.63^{a}	48.86^{d}
Sorghum BD-731	105.51^{b}	31.34^{b}	45.39^{b}	68.50^{b}
Sorghum BD-733	104.33^{bc}	58.97^{ab}	48.39^{b}	66.32^{bc}
Sorghum BD-737	115.09^{a}	43.49^{ab}	83.33^{ab}	57.04^{cd}
LSD	9.1145	55.389	38.871	10.417
CV (%)	5.33	59.12	27.67	9.2

Means bearing the dissimilar letter within the column differ significantly

3.4 Biomass Partitioning and Dry Matter Retention

Salinity stress significantly reduced biomass accumulation across plant organs (Table 4). At 100 DAS, total dry weight indices (TDWI) for BD-737, BD-730, and BD-731 exceeded 78%, contrasting starkly with Hybrid Sorgo and BD-701 (<25%). This retention underscores these genotypes' capacity for carbon assimilation under osmotic challenge (Parida and Das, 2005). Notably, root dry weight displayed the highest coefficient of variation (110%), reflecting differential root-based tolerance strategies (Ahmad et al., 2015).

Table 4: Index of root, stem and leaf dry weight of ten Sorghum germplasm grown at control and salinity conditions in pot

Germplasm	Index of dry weight of stressed plant over control							
	At 70 DAS				At 100 DAS			
	Root Dry Weight Index (RDWI)	Stem Dry Weight Index (SFWI)	Leaf Dry Weight Index (LDWI)	Total Dry Weight Index (TDWI)	Root Dry Weight Index (RDWI)	Stem Dry Weight Index (SFWI)	Leaf Dry Weight Index (LDWI)	Total Dry Weight Index (TDWI)
Hybrid Sorgo	26.20^{ef}	16.42^{h}	54.75^{c}	27.01^{ef}	6.68^{c}	27.96^{d}	53.60^{e}	22.34^{cd}
Sorghum BD-701	13.47^{fg}	37.97^{ef}	53.74^{c}	37.43^{e}	9.21^{c}	19.83^{de}	39.87^{g}	20.31^{d}
Sorghum BD-703	35.09^{cde}	18.39^{gh}	27.18^{d}	23.10^{f}	74.26^{abc}	8.35^{e}	47.05^{f}	31.85^{cd}
Sorghum BD-706	30.68^{de}	78.40^{bc}	92.19^{ab}	71.11^{bc}	15.65^{c}	72.57^{b}	101.24^{a}	63.65^{b}
Sorghum BD-713	10.17^{g}	100.07^{a}	100.75^{a}	77.07^{b}	33.71^{bc}	19.18^{de}	70.35^{c}	31.63^{cd}
Sorghum BD-720	55.30^{b}	51.23d^{e}	101.41^{a}	63.77^{cd}	18.68^{c}	76.33^{b}	101.24^{a}	68.88^{ab}
Sorghum BD-730	39.47^{cd}	53.94^{d}	79.98^{b}	57.72^{d}	123.01^{a}	101.55^{a}	54.01^{e}	78.36^{a}
Sorghum BD-731	15.23^{fg}	32.11^{fg}	60.14^{c}	34.89^{e}	22.27^{bc}	101.81^{a}	100.04^{a}	79.20^{a}
Sorghum BD-733	45.90^{bc}	70.27^{c}	100.20^{a}	76.58^{b}	10.72^{c}	53.32^{c}	60.04^{d}	35.90^{c}
Sorghum BD-737	79.88^{a}	87.92^{ab}	100.06^{a}	91.39^{a}	98.24^{ab}	77.90^{b}	87.98^{b}	81.83^{a}
LSD	13.148	15.416	17.272	11.411	77.845	13.804	4.0181	14.437
CV (%)	21.81	16.44	13.07	11.88	110.03	14.4	3.27	16.37

Means bearing the dissimilar letter within the column differ significantly

3.5 Osmolyte Accumulation: Proline Dynamics

Proline accumulation at 70 and 90 DAS (Figures 1 and 2) significantly increased under salinity in all genotypes, with BD-737 and BD-730 showing 2-3-fold higher levels than controls. This osmo protective response facilitates cellular osmotic balance and reactive oxygen species (ROS) scavenging (Szabados and Savouré, 2010; Ashraf and Foolad, 2007). The strong positive correlation (r = 0.82) between proline content and TDWI suggests that osmolyte synthesis is integral to biomass preservation under salt stress.

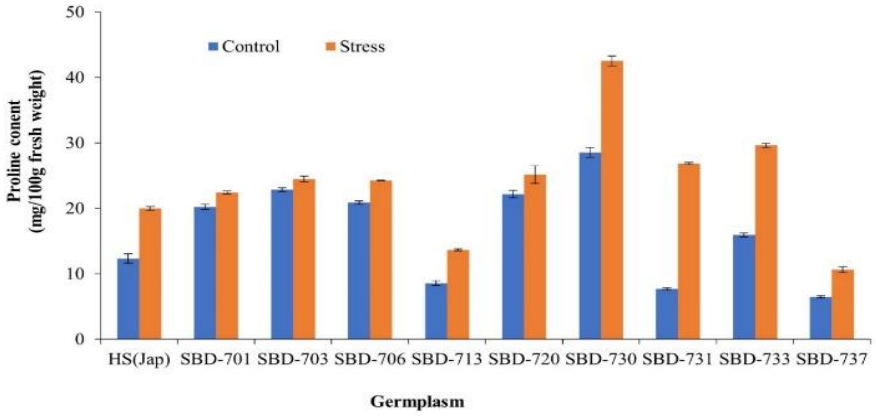


Figure 1: Proline content (mg/100g fresh weight) of ten Sorghum germplasm at 70 DAS under control and stressed condition in pot

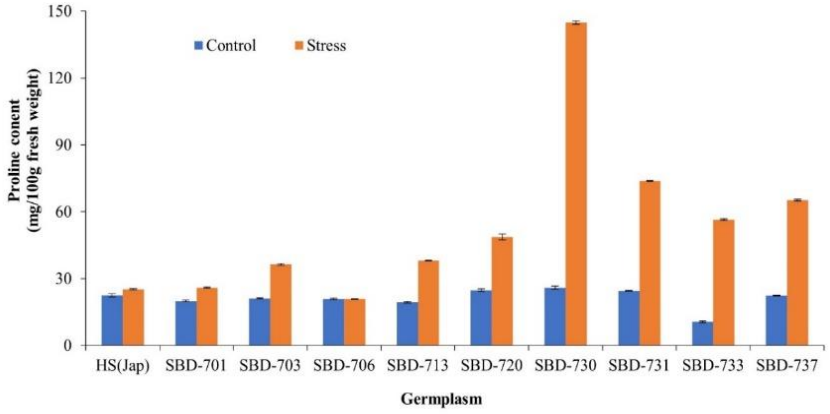


Figure 2: Proline content (mg/100g fresh weight) of ten Sorghum germplasm at 90 DAS under control and stressed condition grown in pot

3.6 Ion homeostasis and selective partitioning

Salinity markedly altered Na^+ and K^+ concentrations (Tables 5 and 6), with genotype-dependent partitioning strategies. BD-730 exhibited the lowest root and total Na^+ accumulation (27.9 mg and 87.3 mg, respectively) and the highest K^+/Na^+ ratio (63.2), indicating efficient Na^+ exclusion and K^+ retention as key tolerance mechanisms (Shabala and Cuin, 2008; Davenport et al., 2007). Conversely, BD-703 recorded elevated Na^+/Ca^{2+} ratios (>3400), reflecting disrupted ionic balance and membrane destabilization. Genotypes BD-706 and BD-720 accumulated higher Ca^{2+} (176.7 and 111.0 mg, respectively) and Mg^{2+}, which may reinforce cell wall integrity and enzyme function under stress (White and Broadley, 2003). The Na^+/Ca^{2+} ratio emerged as a robust indicator of membrane selectivity, with lower values correlating with improved growth indices.

3.7 Integrated Tolerance Mechanisms

Cluster analysis of multi-trait indices placed BD-737, BD-730, and BD-731 in a high-tolerance group, characterized by superior growth retention, osmolyte accumulation, and ionic homeostasis. These genotypes represent promising candidates for salt-tolerant breeding programs and warrant further field validation in saline soils (Mitra et al., 2010).

Table 5: Index of Na^+ and K^+ partitioning at 100 DAS in salinity stressed Sorghum plant over control in pot culture

Germplasm	Index of Na^+ content (mg) at 100 DAS			Index of K^+ content (mg) at 100 DAS		
	Root	Stem	Leaf	Root	Stem	Leaf
Hybrid Sorgo	17.97^{b}	708.60^{de}	621.50^{d}	1.25^{c}	12.95^{ef}	52.10^{g}
Sorghum BD-701	40.35^{b}	329.50^{ef}	377.0^{f}	5.19^{c}	20.92^{e}	45.26^{h}
Sorghum BD-703	405.37^{ab}	158.0^{ef}	1092.0^{b}	13.07^{bc}	6.79^{f}	48.32^{h}
Sorghum BD-706	150.40^{b}	3218.90^{ab}	766.40^{c}	4.41^{c}	67.11^{b}	70.01^{d}
Sorghum BD-713	447.44^{ab}	580.30^{def}	671.60^{cd}	4.83^{c}	6.16^{f}	39.07^{i}
Sorghum BD-720	75.91^{b}	2645.20^{bc}	346.60^{f}	7.18^{c}	177.95^{a}	60.76^{e}
Sorghum BD-730	27.85^{b}	21.60^{f}	608.80^{de}	78.05^{a}	63.35^{b}	56.51^{f}
Sorghum BD-731	244.39^{ab}	2510.0^{c}	513.30^{e}	4.22^{c}	37.24^{d}	75.56^{c}
Sorghum BD-733	42.65^{b}	3409.60^{a}	2156.70^{a}	3.26^{c}	49.01^{c}	80.04^{b}
Sorghum BD-737	918.36^{a}	954.50^{d}	1082.70^{b}	47.42^{ab}	66.99^{b}	117.97^{a}
LSD	733.09	578.19	103.79	37.233	9.837	3.4206
CV (%)	180.27	23.19	7.35	128.53	11.28	3.09

Means bearing the dissimilar letter within the column differ significantly

Table 6: Index of total Na^+, K^+, Ca^{++} and Mg^{++} content at 100 DAS along with their ratio in salinity stressed Sorghum plants over control in pot culture at BAU, Mymensingh

Germplasm	At 100 days after sowing						
	Total Na^+ content (mg)	Total K^+ content (mg)	Total Ca^{++} content (mg)	Total Mg^{++} content (mg)	K^+/Na^+	Na^+/Ca^{++}	Na^+/Mg^{++}
Hybrid Sorgo	216.1^{de}	26.53^{f}	82.67^{e}	43.14f^{g}	12.13^{ef}	261.70^{fg}	501.90^{e}
Sorghum BD-701	198.8^{e}	57.69^{ef}	31.82^{g}	34.83^{g}	29.02^{b}	624.7^{e}	570.80^{de}
Sorghum BD-703	377.9^{de}	41.96^{ef}	10.99^{h}	47.95^{efg}	11.1^{f}	3437.0^{a}	788.0^{cd}
Sorghum BD-706	1106.8^{ab}	139.96^{c}	176.66^{b}	62.87^{cde}	12.60^{ef}	627.3^{de}	1762.70^{a}
Sorghum BD-713	563.7^{cd}	72.50^{de}	55.82^{f}	51.27^{def}	13.33^{ef}	1003.80^{c}	1080.20^{b}
Sorghum BD-720	1204.5^{a}	242.34^{a}	110.98^{d}	66.35^{cd}	20.12^{cd}	1086.0^{c}	1815.60^{a}
Sorghum BD-730	87.3^{e}	55.0^{ef}	146.60^{c}	74.67b^{c}	63.24^{a}	60.10^{g}	118.60^{f}
Sorghum BD-731	1077.5^{ab}	109.34^{cd}	197.85^{a}	123.80^{a}	10.14^{f}	544.30^{ef}	870.40^{bc}
Sorghum BD-733	808.2^{bc}	131.80^{c}	47.92^{f}	46.26f^{g}	16.31^{de}	1676.30^{b}	1744.5^{a}
Sorghum BD-737	923.8^{ab}	186.12^{b}	92.55^{e}	88.36^{b}	22.35^{c}	964.0^{cd}	987.20^{bc}
LSD	353.25	39.634	10.596	15.514	5.1682	338.48	264.66
CV (%)	31.37	21.73	6.48	14.14	14.32	19.18	15.07

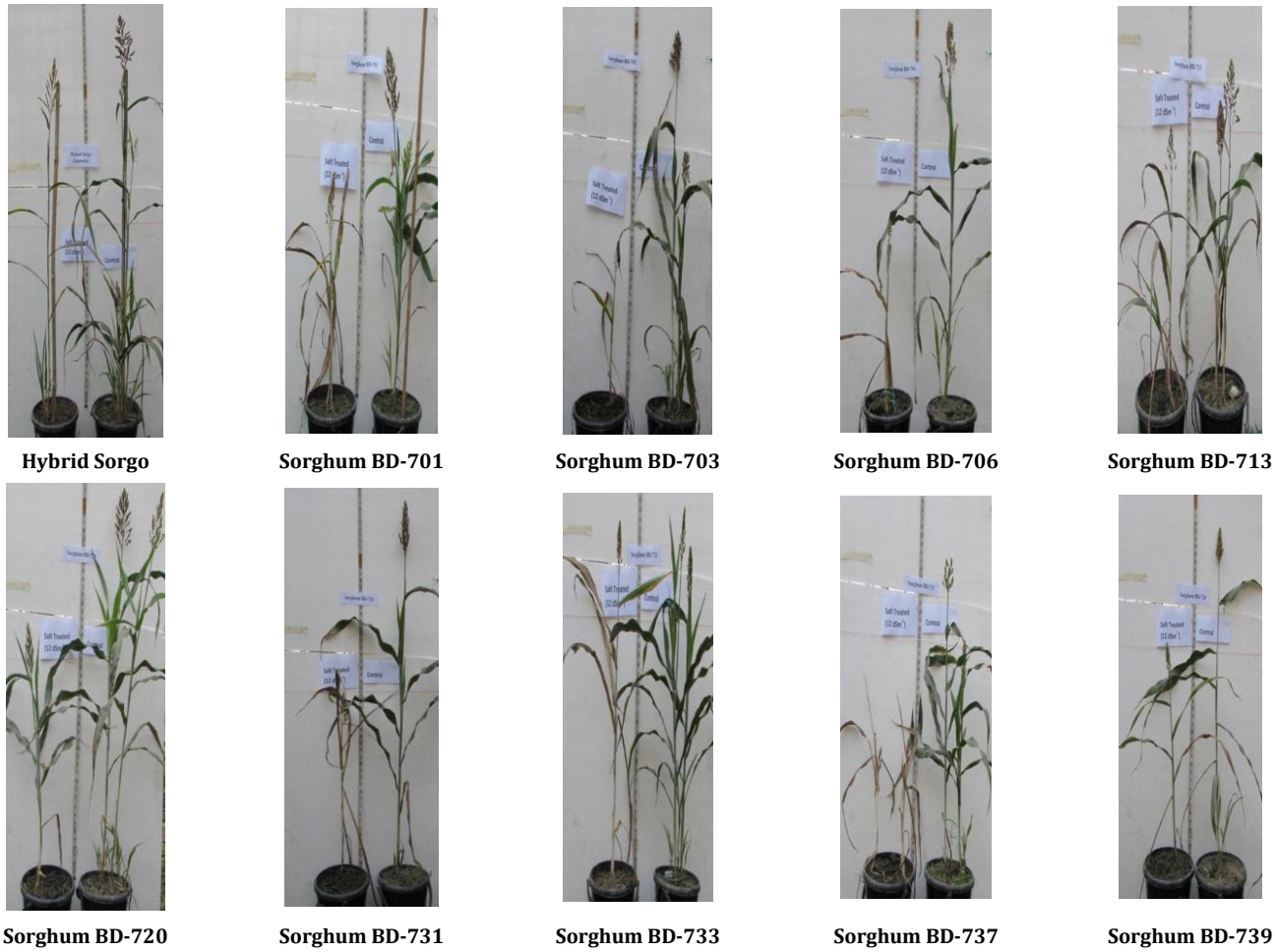
Means bearing the dissimilar letter within the column differ significantly

3.8 Morphological responses

Under control (0 dS m^{-1}) conditions all ten sorghum germplasm exhibited similar vigour (Plate 1, left panels). However, exposure to 12 dS m^{-1} salinity stress led to genotype-dependent reductions in growth (Plate 1, right panels). Plant height reductions ranged from 18 % in BD-737 to 52 % in BD-731 (Table 1). Similarly, root length declined by 15-48 % across genotypes, with BD-706 and BD-713 showing moderate tolerance (25-30 % reduction) and BD-731, BD-739 the greatest sensitivity (>40 % reduction) (Table 1). Fresh and dry biomass followed the same trend: BD-737 retained 62 % of its control biomass, while BD-731 retained only 38 % (Table 1).

3.9 Physio-chemical responses

Leaf chlorophyll content decreased under salinity by 12-40 %, with tolerant accessions BD-737 and BD-733 maintaining >75 % of control chlorophyll, whereas sensitive BD-731 and BD-739 dropped below 60 % (Table 2). Proline accumulation increased markedly in all genotypes, but the magnitude varied: BD-720 and BD-706 accumulated up to 3.8-fold more proline, compared to 2.1-fold in BD-731 (Table 2). Na^+ concentration in leaf tissues rose from 12–18 mg g^{-1} DW under control to 35-48 mg g^{-1} DW under stress; potassium (K^+) showed the opposite trend, declining from 35-42 mg g^{-1} to 21-28 mg g^{-1} (Table 2). Consequently, the K^+/Na^+ ratio under salt stress dropped most severely in BD-731 (from 2.8 to 0.6) and least in BD-737 (from 3.0 to 1.2).



Hybrid Sorgo | **Sorghum BD-701** | **Sorghum BD-703** | **Sorghum BD-706** | **Sorghum BD-713**

Sorghum BD-720 | **Sorghum BD-731** | **Sorghum BD-733** | **Sorghum BD-737** | **Sorghum BD-739**

Plate 1: Comparative growing condition of 10 Sorghum germplasm under control and salinity stress (12 dSm^{-1}) grown in pot at the Grill House of Department of Crop Botany, Bangladesh Agricultural University, Mymensingh

Cite The Article: Md. Eakramul Haque, Md. Rishad Abdullah, A.K.M. Golam Sarwar, Md.Akhter-Ul-Alam, Md. Al-Amin Hossain Talukder, Biplob Kumar Saha, A.K.M. Zakir Hossain (2025). Morpho-Physiological and Biochemical Responses of Sorghum Germplasm to Salinity Stress Under Pot Culture. *Plant Physiology and Soil Chemistry, 5(2): 105-111.*

4. Conclusions

The comprehensive evaluation of ten sorghum genotypes under controlled pot culture conditions has demonstrated marked genotypic variability in salinity tolerance mechanisms. Morphological assessments revealed that BD-737, BD-730, and BD-731 consistently maintained higher leaf number, plant height, and reproductive organ dimensions under saline stress, while biomass partitioning data confirmed their superior dry matter retention. Physiological analyses underscored the critical role of proline accumulation in osmotic adjustment, with these genotypes exhibiting significantly elevated proline levels correlating strongly with biomass indices. Ion homeostasis studies further identified BD-730 as an exemplary Na^+-excluder and K^+-retainer and highlighted the importance of balanced Ca^{2+} and Mg^{2+} accumulation in membrane stabilization. Taken together, the integrated trait analysis positions BD-737, BD-730, and BD-731 as prime candidates for incorporation into breeding programs aimed at developing salt-tolerant sorghum cultivars. Future work should focus on field validation in saline soils and molecular dissection of underlying tolerance loci to accelerate cultivar deployment in salt-affected agroecosystems.

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