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Short communication

Seeds Priming with Gibberellic Acid Enhances Germination and Early Seedling Growth under Salinity Stress in Maize (*Zea Mays* L.)

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A gibberellic acid priming study was conducted at laboratory conditions of Khulna University, Bangladesh, using the maize variety, 'BARI Hybrid Bhutta-16', during 2021. The treatments consisted of four salinity levels with electrical conductivities (ECs) of 0, 10, 20, and 30 dS/m, combined with three GA_3 concentrations (0, 100 and 150 ppm). Salinity stress significantly impaired germination percentage, germination energy, and germination speed, as well as root and shoot development, particularly at salinity levels exceeding EC of 10 dS/m. GA_3 application improved seedling growth across salinity levels, with 100 and 150 ppm concentrations showing the most notable effects under EC of 10 dS/m. Root and shoot lengths, fresh and dry biomass, and seedling vigour index were enhanced by GA_3 treatment, especially at EC of 0 – 10 dS/m. However, at ECs of 20 and 30 dS/m, GA_3 failed to significantly improve most of the parameters, indicating a threshold beyond which salt stress overrides hormonal benefits. GA_3 priming enhances maize germination and early seedling growth under moderate salinity but shows limited efficacy under severe stress.

Keywords: maize, salinity stress, gibberellic acid, seedling growth, germination parameters, BARI Hybrid Bhutta-16

Maize (*Zea mays* L.), a member of the family Poaceae, is one of the most important food grains in the world, as well as in developing countries like Bangladesh, where the crop is popularly known as 'bhutta'. The United States is by far the world's largest producer of maize grain with 2022 – 2023 production of 346.74 million (M) metric tons from 35.01 M ha with 11.13 t/ha average yield followed by China with 2022 – 2023 production of 277.20 M metric tons from the acreage of 44.22 M ha with 6.53 t/ha average yield (Anon. 2025). About 5.63 million metric tons of maize grain is produced from 0.55 million hectares with an average yield of 10.24 t/ha in Bangladesh during 2021 – 2022, which is due to the introduction of hybrids and adoption of appropriate crop management practices (Sarker *et al.* 2023). Demand for maize is increasing in Bangladesh day by day due to the increasing demand for poultry, fish, and animal feed, and the production of different types of processed foods, and for export.

Among abiotic stresses, soil salinity is one of the major factors limiting crop growth and productivity. It is estimated that about 6% of the total arable land worldwide is affected by soil salinity (Ahmad

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2010). Soil salinity not only decreases the seed emergence and germination rates but also severely reduces the growth, development, and yield of field crops (Gill *et al.* 2013; Saade *et al.* 2016). Salinity stress negatively impacts maize production by hindering growth and reducing yield. Since maize is a C_4 plant, it exhibits some tolerance to salinity; its early growth stages are particularly sensitive to high salt concentrations (Anon. 2023).

Because of this crop's moderate sensitivity to salt stress, soil salinity poses a severe danger to the global production of maize. Salt-affected soils, defined by electrical conductivity (EC) ≥ 4 dS/m, equivalent to 40 mM or exchangeable sodium percentage (ESP) ≥ 15% (Shahid *et al.* 2018), currently impair over 800 million hectares globally, including 397 million hectares saline and 434 million hectares sodic (Toderich & Tsunekawa 2021). Salinity inflicts multi-phase damage in maize, including initial osmotic stress that reduces water uptake within hours, followed by cytotoxic Na^+ and Cl^- accumulation that disrupts K^+ homeostasis and nitrogen assimilation (Zhao *et al.* 2010; Atta *et al.* 2023). Germination assays reveal salinity thresholds as low as EC of 5 dS/m salinity (50 mM NaCl) that reduce radicle emergence by 40 – 60%, with critical yield losses attributed to diminished kernel weight (18 – 32%) in maize (Hütsch *et al.* 2014).

Phytohormones mediating stress tolerance are crucial in plants' response to salinity stress to withstand constant stressful conditions. As phytohormone makes a great contribution in mitigating salinity stress and help plants adapt to this type of stress, nine plant hormones, namely auxins, gibberellins, cytokinins, brassinosteroids, strigolactones, ethylene, abscisic acid, salicylic acid, and jasmonic acid (Yu *et al.* 2020). Among these, gibberellic acid (GA_3) has emerged as a potent mitigator of salt stress through its dual role in growth promotion and osmotic adjustment (El-Nwehy & Afify 2023). Application of 10 – 100 ppm GA_3 demonstrates dose-dependent efficacy; seed priming with 100 ppm GA_3 in saline soils (EC of 8 dS/m) improves maize germination rates by 33% and shoot biomass by 47% (Geilfus *et al.* 2010; El-Nwehy & Afify 2023). Rauf *et al.* (2022) reported that 2 mM GA_3 recorded the maximum germination percentage, shoot and root length, shoot and root fresh and dry weight, and seed vigour index. Zhu *et al.* (2019) concluded that the 288 μM (100 ppm) GA_3 is the optimum concentration that promoted seed germination, radicle, and plumule length of sweet sorghum under salinity stress conditions.

Waleed *et al.* (2019) obtained maximum germination [%] as well as other germination properties, shoot and root length, shoot and root dry weight, and seedling vigour index when wheat seeds are soaked with 150 ppm GA_3 before sowing under salinity stress.

Among the hybrid maize varieties found in Bangladesh, 'BARI Hybrid Bhutta-16' has the potential to produce 10 – 12 tons of grain/ha (Sarkar *et al.* 2023). However, salinity and GA_3 effects have not been previously investigated on this hybrid maize variety. The experiment was, therefore, conducted to study the influence of GA_3 on germination and germination parameters and early seedling growth under salinity stress.

The experiment was conducted in the Agronomy Laboratory of the Agrotechnology Discipline of Khulna University, Bangladesh (22°48'8.93" N latitude and 89°31'57.33" E longitude) from August 2021 to November 2021. Seeds of maize var. 'BARI Hybrid Bhutta-16' (BML-59 × BML-71) was collected from the Bangladesh Wheat and Maize Research Institute, Dinajpur, Bangladesh. Seeds were surface sterilised with 0.1% mercuric chloride ($HgCl_2$) solution for 10 min. Then, the seeds were washed several times with distilled water to eliminate excess solution of $HgCl_2$. The seeds were then air-dried at room temperature (25°C) for 30 min.

A 3 × 4 factorial completely randomised design (CRD) was followed by three replications. The treatments consisted of three GA_3 solutions, viz. 0, 100 and 200 ppm designated as G_0, G_1 and G_2, and four salinity levels viz. ECs of 0, 10, 20, and 30 dS/m designated as S_0, S_1, S_2, and S_3. For priming, seeds were soaked in GA_3 solutions separately at three concentrations, viz. 0, 100 and 150 ppm designated as G_0, G_1 and G_2 for 24 h before placing the seeds in Petri dishes. After priming, seeds were collected and kept under shade for air drying. For priming, seeds were soaked in GA_3 solutions separately at three concentrations, viz. 0, 100 and 150 ppm designated as G_0, G_1 and G_2 for 24 h before placing the seeds in Petri dishes. After priming, seeds were collected and kept under shade for air drying. For priming, seeds were soaked in GA_3 solutions separately at three concentrations, viz. 0, 100 and 150 ppm designated as G_0, G_1 and G_2 for 24 h before placing the seeds in Petri dishes. After priming, seeds were collected and kept under shade for air drying.

For each treatment combination, four glass Petri dishes (9 cm diameter) were used, each having twelve seeds. Each Petri dish was lined with three layers of filter paper (Whatman # 1). Therefore, a total of 144 (3 × 4 × 4 × 3) Petri dishes were required. After placing the GA_3 primed seeds in Petri dishes lined with filter papers, the filter papers were moistened with 6 mL of the respective NaCl salt solution, and a cover was placed over each Petri dish to prevent evaporation loss of salt solution. Moisture was maintained by regular supplementation, ensuring no standing water remained in the Petri dishes.

Seed germination and seedling growth parameters were assessed after 15 days of seed sowing in Petri dishes. Germination percentage, germination capacity (at 168 h), germination energy (at 72 h), and germination speed were calculated using standard formulae (Nasrin & Mannan 2019), as follows:

$$\text{Germination [\%]} = \frac{\text{Number of seeds germinated after 15 days}}{\text{Total number of seeds set for test}} \times 100$$

$$\text{Germination energy [\%]} = \frac{\text{Number of seeds germinated at 72 h}}{\text{Total number of seeds set for test}} \times 100$$

$$\text{Germination speed [\%]} = \frac{\text{Number of seeds germinated at 72 h}}{\text{Total number of seeds germinated at 168 h}} \times 100$$

Seedling vigour index = (Mean shoot length + Mean root length) × Germination percentage (Zhao *et al.* 2016)

The seedling vigour index was determined as the product of the sum of average shoot and root lengths and the germination percentage. Eight seedlings from each treatment were randomly selected for measurement. Root and shoot lengths were measured from the collar region to the respective tips. Fresh weights of roots and shoots were recorded immediately after harvest, while dry weights for the same were obtained after oven-drying the samples at 70°C for 24 h.

All data were subjected to analysis of variance (ANOVA) using the Statistix 10 software package. Mean comparisons were performed using Duncan's new multiple range test (DMRT) at both 1% and 5% levels of significance. The assumptions of normality and homogeneity of variance were checked before analysis to ensure the validity of the results.

RESULTS

Germination Parameters

Germination percentage, germination energy and germination speed were significantly influenced by salinity levels alone but not by GA_3 levels independently (Table 1). Salinity levels at ECs of 20 and 30 dS/m reduced germination [%] compared to the control. The maximum germination (90.50%) was recorded in the control, which was statistically similar to EC of 10 dS/m (87.50%), and the lowest germination [%] was found at EC of 20 dS/m (82.87%), closely followed by EC of 30 dS/m (84.49%). The combination of salinity and GA_3 levels also significantly influenced germination [%] (Table 2). Under control salinity (EC of 0.0 dS/m), the highest germination (91.67%) was recorded at both 100 and 150 ppm GA_3, but no significant difference was found among the three GA_3 levels. At EC of 10 dS/m salinity levels, seeds priming with 150 ppm GA_3 gave the highest germination (89.58%), being identical with 0.0 ppm GA_3 (86.11%) and 100 ppm GA_3 (86.80%). Under EC of 20 dS/m, the maximum germination (89.58%) was observed at 150 ppm $GA_{3,}$ and the minimum was found at 100 ppm $GA_{3,}$ being identical with the control GA_3. But at the highest level of salinity (EC of 30 dS/m), no encouraging result was found from GA_3 seed priming regarding germination percentage.

Germination energy was decreased with the increase of salinity stress up to 20 dS/m salinity levels, then increased slightly at EC of 30 dS/m (Table 1). The maximum germination energy (84.02%) was found at control salinity (EC of 0.0 dS/m), which was statistically similar to EC of 10 dS/m (80.78%), and the minimal germination energy (72.91%) was noted at EC of 20 dS/m salinity level, closely followed by EC of 30 dS/m (73.61%). Germination energy was significantly affected by the combined effect of salinity stress and GA_3 levels (Table 2). At normal (saline-free) conditions, although the highest germination energy (84.72%) was obtained from 150 ppm GA_3, there was no significant difference found among 0.0, 100 and 150 ppm GA_3. Under EC of 10 dS/m salinity stress, no significant difference was observed among 0.0, 100 and 150 ppm GA_3, though maximum germination energy (81.94%) was recorded at 100 ppm GA_3. At ECs of 20 and 30 dS/m salinity stress, the highest germination energy (81.94 and 72.91%) was observed when seeds were primed with 150 ppm GA_3.

Germination speed was reduced gradually with the increase of salinity stress (Table 1). The maximum germination speed (92.92%) was found at normal (saline-free) salinity, which was identical with ECs of 10 and 20 dS/m salinity levels (92.30 and 87.83%), and the minimum was recorded at EC of 30 dS/m salinity levels. Salinity stress in combination with GA_3 priming significantly influenced the germination speed (Table 2). GA_3 priming seeds had no significant effect on saline-free conditions, and a similar effect of GA_3 was also found at an EC of 10 dS/m salinity level. Under ECs of 20 and 30 dS/m salinity stress conditions, the highest germination speed was observed at 150 ppm GA_3 (91.44 and 89.55%).

Seedling Growth Parameters

Seedling growth parameters, except root fresh weight, were significantly affected by salinity levels (Table 3). Shoot length, root and shoot fresh weight,

T a b l e 1

Effect of salinity and GA_3 levels on seed germination parameters of hybrid maize var. 'BARI Hybrid Bhutta-16'

Parameters	Salinity levels [dS/m]				*CV* [%]	*p*	GA_3 levels [ppm]			*CV* [%]	*p*
	S_0	S_1	S_2	S_3			G_0	G_1	G_2		
Germination [%]	90.50^{a}	87.50^{ab}	82.87^{b}	84.49^{b}	6.37	+	85.59	85.41	88.02	6.37	ns
Germination energy [%]	84.02^{a}	80.78^{ab}	72.91^{c}	73.61^{bc}	9.85	+	78.12	75.17	80.20	9.85	ns
Germination speed [%]	92.92^{a}	92.3^{ab}	87.83^{ab}	86.74^{b}	6.47	+	91.16	87.67	91.06	6.47	ns

The values in the same row with different superscript letters are significantly different at the $p<0.01$ level for each variable by DMRT.
S_0= 0 dS/m, S_1= 10 dS/m, S_2= 20 dS/m, S_3= 30 dS/m, G_0= 0 ppm, G_1= 100 ppm, G_2= 150 ppm
CV – coefficient of variance; *p* – level of significance; +significant at 95% confidence interval; ns – non-significant; DMRT – Duncan's new multiple range test; BARI – Bangladesh Agricultural Research Institute.

T a b l e 2

Interaction effect of salinity and GA_3 levels on seed germination parameters of hybrid maize var. 'BARI Hybrid Bhutta-16'

Parameters	Salinity levels/GA_3 levels												CV [%]	*p*
	S_0			S_1			S_2			S_3				
	G_0	G_1	G_2	G_0	G_1	G_2	G_0	G_1	G_2	G_0	G_1	G_2		
Germination [%]	88.19^{a-c}	91.67^{a}	91.67^{a}	86.11^{a-c}	86.80^{a-c}	89.58^{ab}	79.86^{c}	79.17^{c}	89.58^{ab}	88.19^{a-c}	84.03^{a-c}	81.25^{bc}	6.37	+
Germination energy [%]	83.33^{ab}	84.03^{a}	84.72^{a}	79.17^{a-c}	81.94^{ab}	81.25^{a-c}	70.83^{b-d}	65.97^{d}	81.94^{ab}	79.17^{a-c}	68.747^{cd}	72.917^{a-d}	9.85	+
Germination speed [%]	94.63^{a}	91.65^{ab}	92.49^{ab}	91.95^{ab}	94.34^{a}	90.78^{a-c}	88.94^{a-c}	83.12^{bc}	91.44^{ab}	89.11^{a-c}	81.58^{c}	89.547^{a-c}	6.47	+

The values in the same row with different superscript letters are significantly different at the $p<0.01$ level for each variable by DMRT.
S_0= 0 dS/m, S_1= 10 dS/m, S_2= 20 dS/m, S_3= 30 dS/m, G_0= 0 ppm, G_1= 100 ppm, G_2= 150 ppm
CV – coefficient of variance; *p* – level of significance; $^{+}$significant at 95% confidence interval; DMRT – see Table 1; BARI – see Table 1.

and root and shoot dry weight, except root length, shoot fresh weight, and seedling vigour index were significantly influenced by GA_3 levels (Table 3). Seedling growth parameters (root length, shoot length, root fresh weight, shoot fresh weight, shoot dry weight, and seedling vigour index) were decreased gradually with the increased salinity levels, whereas root dry weight was reduced up to EC of 20 dS/m. The longest root (17.72 cm) and shoot (38.65 cm) were recorded under control conditions (EC of 0 dS/m salinity and the least root and shoot length were found in 30 dS/m. The maximum shoot fresh weight (0.8 g) was noted in control salinity, and the minimal shoot fresh weight was from the highest salinity levels (EC of 30 dS/m). The highest root dry weight (67 mg) was recorded in control salinity, which was statistically similar to ECs of 10 and 30 dS/m salinity levels. Shoot dry weight (73 mg) was found to be highest from EC of 0.0 dS/m salinity, closely followed by EC of 10 dS/m (70.4 mg). The control salinity gave the maximum seedling vigour index of 5,101.5, and the EC of 30 dS/m recorded the minimal seedling vigour index of 2,839.7.

Seeds primed with 150 ppm GA_3 produced the maximum shoot length (34.28 cm), being identical with 100 ppm GA^3 (34.08 cm) (Table 3). Root fresh weight and root dry weight were recorded as the highest from 0.0 ppm GA_3, which were identical with 150 ppm GA_3.

A significant interaction between salinity and GA_3 levels was observed across all parameters (Table 4). At EC of 0.0 dS/m salinity, 0.0 ppm GA_3 gave the highest root length (19.75 cm), being identical with 150 ppm GA_3 (17.35 cm). Under ECs of 10, 20 and 30 dS/m salinity, seeds primed with GA_3 levels (100 and 150 ppm) gave no encouraging result regarding root length. In the case of shoot length under all salinity levels, seeds primed with 150 ppm gave better results. In the case of root fresh weight, under ECs of 10 and 30 dS/m, 150 ppm GA_3 performed better. Regarding shoot fresh weight, at EC of 10 dS/m salinity levels, 100 and 150 ppm GA_3 gave better results. Root dry weight was found to be better at 100 and 150 ppm GA_3 under all salinity levels. Under controlled salinity and EC of 10 dS/m, both 100 and 150 ppm gave better results with respect to shoot dry weight. Regarding the seedling vigour index, at EC of 10 dS/m salinity levels, both 100 and 150 ppm recorded better results. In this study, a broad range of salinity levels (10, 20 and 30 dS/m) was applied, revealing that 100 and 150 ppm GA_3 treatment can alleviate the negative effects of salinity on seedling growth up to moderate levels (EC of 10 dS/m), but is largely ineffective under severe salt stress (ECs of 20 and 30 dS/m).

Table 3

Effect of salinity and GA_3 levels on seedling growth parameters of hybrid maize var. 'BARI Hybrid Bhutta-16'

Parameters	Salinity levels [dS/m]				*CV* [%]	*p*	GA_3 levels [ppm]			*CV* [%]	*p*
	S_0	S_1	S_2	S_3			G_0	G_1	G_2		
Root length [cm]	17.72^a	12.61^b	10.06^c	9.42^c	14.08	+	13.13	12.15	12.09	14.08	ns
Shoot length [cm]	38.65^a	35.43^b	28.05^c	24.19^d	6.70	+	26.39^b	34.08^a	34.28^a	6.70	+
Root fresh weight [g]	0.48	0.45	0.44	0.44	15.83	NS	0.49^a	0.40^b	0.45^{ab}	15.83	+
Shoot fresh weight [g]	0.83^a	0.69^b	0.48^c	0.43^c	13.17	+	0.61	0.59	0.64	13.17	ns
Root dry weight [mg]	67.00^a	63.00^{ab}	55.00^b	61.00^b	13.16	+	66.00^a	58.00^b	62.00^{ab}	13.16	+
Shoot dry weight [mg]	73.00^a	70.40^a	49.80^b	49.50^b	13.40	+	57.00^b	64.00^a	62.00^a	13.40	+
Seedling vigour index	5,101.5^a	4,203.5^b	3,158.2^c	2,839.7^c	15.70	+	3,382.5	3,948.5	4,081.5	15.70	ns

The values in the same row with different superscript letters are significantly different at the $p < 0.01$ level for each variable by DMRT.
S_0= 0 dS/m, S_1= 10 dS/m, S_2= 20 dS/m, S_3= 30 dS/m, G_0= 0 ppm, G_1= 100 ppm, G_2= 150 ppm
CV – coefficient of variance; *p* – level of significance; +significant at 1% level of probability; ns – non-significant; DMRT – see Table 1; BARI – see Table 1.

T a b l e 4

Interaction effect of salinity and gibberellic acid levels on seedling growth parameters of hybrid maize var. 'BARI Hybrid Bhutta-16'

Parameters	Salinity levels/GA_3 levels												*CV* [%]	*p*
	S_0			S_1	S_2				S_3					
	G_0	G_1	G_2	G_0	G_1	G_2	G_0	G_1	G_2	G_0	G_1	G_2		
Root length [cm]	19.75^{a}	16.06^{b}	17.35^{ab}	12.15^{c-e}	13.08^{c}	12.63^{cd}	10.10^{d-f}	10.60^{c-f}	9.48^{ef}	10.50^{c-f}	8.88^{f}	8.90^{f}	14.08	+
Shoot length [cm]	31.16^{c}	42.17^{a}	42.63^{a}	28.90^{cd}	37.77^{b}	39.60^{ab}	23.50^{ef}	31.98^{c}	28.60^{cd}	21.92^{f}	24.40^{ef}	26.30^{de}	6.70	+
Root fresh weight [g]	0.53^{a}	0.32^{c}	0.46^{ab}	0.44^{ab}	0.48^{ab}	0.458^{ab}	0.48^{ab}	0.44^{ab}	0.39^{bc}	0.54^{a}	0.40^{bc}	0.51^{ab}	15.83	+
Shoot fresh weight [g]	0.85^{a}	0.79^{ab}	0.86^{a}	0.68^{b}	0.66^{b}	0.76^{ab}	0.49^{c}	0.52^{c}	0.40^{c}	0.446^{c}	0.39^{c}	0.47^{c}	13.17	+
Root dry weight [mg]	74.00^{a}	60.40^{a-c}	69.00^{ab}	65.00^{a-c}	61.00^{a-c}	63.00^{a-c}	57.00^{bc}	58.00^{bc}	53.00^{c}	67.00^{00b}	52.00^{c}	64.00^{a-c}	13.16	+
Shoot dry weight [mg]	67.10^{ab}	75.80^{a}	79.00^{a}	60.00^{bc}	76.00^{a}	75.00^{a}	50.00^{cd}	54.00^{b-d}	46.00^{d}	51.00^{cd}	48.80^{cd}	49.20^{cd}	13.40	+
Seedling vigour index	$4,489.8^{a}$	$5,337.9^{a}$	$5,498.4^{a}$	$3,534.8^{b-d}$	$4,413.8^{b}$	$4,678.8^{bc}$	$2,683.3^{de}$	$3,371.1^{de}$	$3,411.2^{c-e}$	$2,859.1^{b-e}$	$2,796.5^{e}$	$2,860.0^{e}$	15.70	+

The values in the same row with different superscript letters are significantly different at the $p < 0.01$ level for each variable by DMRT.
S_0= 0 dS/m, S_1= 10 dS/m, S_2= 20 dS/m, S_3= 30 dS/m, G_0= 0 ppm, G_1= 100 ppm, G_2= 150 ppm
CV – coefficient of variance; *p* – level of significance; +significant at 1% level of probability; DMRT – see Table 1; BARI – see Table 1.

DISCUSSION

The findings of this study demonstrate that salinity significantly affects germination and other germination parameters and seedling growth characteristics of the maize variety. 'BARI Hybrid Bhutta-16', while the GA_3 application shows potential for mitigating these adverse effects up to certain salinity thresholds. The observed reduction in germination parameters, such as percentage, energy, and speed, with increasing salinity levels aligns with established research on salt stress in maize (Shahzad *et al.* 2021; Rauf *et al.* 2022). The decline in germination parameters can be attributed to the osmotic effect that prevents water uptake and the ionic toxicity that disrupts normal metabolic activities during germination (de la Reguera *et al.* 2020). Our findings regarding the reduction in seedling growth parameters under saline conditions are consistent with those reported by Rauf *et al.* (2022), who found that salt stress at EC of 15 dS/m significantly reduced shoot and root length, fresh and dry weights, and chlorophyll content in maize seedlings. Similarly, El-Nwehy and Afify (2023) reported that salt stress decreased leaf growth, biomass accumulation, and root and shoot elongation in maize. The more severe impact was observed at higher salinity levels (ECs of 20 − 30 dS/m), indicating the threshold beyond which the stress becomes increasingly detrimental to maize seedling development.

The inconsistent response of germination parameters to GA_3 under different salinity levels highlights the complex interaction between growth regulators and salt stress. While GA_3 improved germination at low to moderate salinity (EC up to 10 dS/m), its effectiveness diminished at higher salinity levels. This pattern has been observed in other studies, where GA_3 enhanced germination parameters under moderate salt stress but showed limited efficacy under severe stress conditions (Chauhan *et al.* 2018; Akhtar *et al.* 2021). Akhtar *et al.* (2021) reported that GA_3 alone or in combination with kinetin alleviated the inhibitory effects of salinity on wheat germination by modulating ion accumulation. The variability in response across different salinity levels suggests that the effectiveness of GA_3 depends on the severity of the stress and possibly the specific physiological mechanisms activated at different stress thresholds (Fu *et al.* 2023). In our findings, GA_3 more effectively promoted shoot elongation than root growth, aligning with the findings of Chauhan *et al.* (2018), who observed that GA_3 application significantly improved shoot length but had less impact on root development in salt-stressed oat seedlings. This differential effect can be attributed to the primary role of GA_3 in promoting cell elongation through the enhancement of cell wall extensibility, a process more pronounced in shoot tissues (Rastogi *et al.* 2013).

The effectiveness of 100 ppm GA_3 in improving seedling growth parameters up to EC of 20 dS/m salinity corroborates the findings of several studies reporting that a combination of GA_3 seed priming and foliar application significantly improved root and shoot length, leaf area, crop growth rate, net assimilation rate, total chlorophyll content, and biomass accumulation in salt-stressed maize (Rasheed *et al.* 2021; Shahzad *et al.* 2021; Islam *et al.* 2024). Similarly, El-Nwehy and Afify (2023) found that 100 ppm GA_3 was the most effective concentration for improving maize growth and development under salt stress. Particularly, GA_3 application at the vegetative stage was found more effective than at the reproductive stage as GA_3 at 50 ppm increased grain yield by 78.8% over drought-stressed controls, primarily by improving cob and seed set (Akter *et al.* 2014).

The less pronounced effect of GA_3 at high salinity levels (ECs of 20 and 30 dS/m) suggests that there are limitations to the stress-mitigating capacity of GA_3 under severe stress conditions, possibly due to overwhelming ionic toxicity and osmotic stress that exceeds the compensatory mechanisms induced by GA_3. While our study focused on seed priming with GA_3, it is worth noting that Shahzad *et al.* (2021) found that combining GA_3 seed priming with foliar application was more effective in improving maize growth under salinity than either method alone. They reported that this combined approach resulted in the highest increase in roots and shoots length (19 − 37%), roots fresh and dry weights (31 − 43%), shoots fresh and dry weights (31 − 47%), and chlorophyll content (21 − 70%) under different salinity levels. Similarly, Hamza and Ali (2017) observed that seedlings from seeds stimulated with GA_3 exhibited greater germination and growth characteristics, along with lower salt-to-potassium ratios and higher chlorophyll content, indicating increased plant tolerance to salinity. However, several limitations must be considered as the experiment was conducted under controlled laboratory conditions, which may not fully capture the complexity of field environments where multiple stresses interact. The study focused only on early growth stages, leaving the long-term effects on yield and crop quality unaddressed; and the effectiveness of GA_3 diminished at very high salinity levels (EC of 30 dS/m), indicating that this strategy has an upper threshold beyond which it is ineffective. Additionally, genotype-specific responses to GA_3 and the risk of over-application potentially leading to growth inhibition highlight the need for further field-based research, optimisation of application protocols, and integration with other agronomic practices for sustainable salinity management (Zhu *et al.* 2019).

CONCLUSIONS

The practical implications of this study suggest that exogenous application of GA_3 can partially alleviate the negative effects of moderate salinity (EC ≤10 dS/m) on the germination and early seedling growth of maize variety 'BARI Hybrid Bhutta-16', which is especially relevant for salt-affected regions in Bangladesh and similar agro-ecological zones in South Asia. The observed improvements in germination energy (81.94% vs. 65.97% at EC of 10 dS/m) and seedling vigour (4,413.8 at EC of 10 dS/m vs. 3,371.1 at EC of 20 dS/m vs 2,796.5 at EC of 30 dS/m) with 100 ppm GA_3 application highlight its role in enhancing early establishment through osmotic adjustment and antioxidant activation. However, the diminished returns under severe salinity (ECs of 20 and 30 dS/m) necessitate integrated strategies combining GA_3 with salt-tolerant germplasm, soil amendments, and precision irrigation to address ionic toxicity. This approach could expand maize cultivation into moderately saline soils, potentially reclaiming 1.2 million hectares of coastal arable land in Bangladesh and reducing substantial yield gaps, thereby enhancing food security and agricultural resilience in salinity-prone areas Future research should prioritize field validations of GA_3 application windows, economic analyses of costs versus yield returns, and molecular studies to identify gibberellic acid-responsive salinity tolerance markers for breeding programs.

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