Interactive Effects of Seed Priming and Salinity Stress on Growth, Yield, and Nutrient Dynamics in Wheat Genotypes (Triticum aestivum L.)

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Abstract

Salinity severely constrains wheat (*Triticum aestivum* L.) productivity in coastal Bangladesh. A split-split plot field experiment at Sher-e-Bangla Agricultural University, Dhaka (November 2017–March 2018) evaluated three varieties (ESWYT 5, ESWYT 6, BARI Gom 28), three NaCl-imposed salinity levels (0, 10, and 15 dS m^{-1}), and three seed priming treatments (no priming; 5% PEG-6000; 2% mannitol). Salinity at 15 dS m^{-1} reduced grain yield by 29%, filled grains $spike^{-1}$ by 45%, 1000-seed weight by 17%, and soil available phosphorus by 40% relative to the non-saline control. ESWYT 5 consistently outperformed BARI Gom 28 across all growth, yield, and nutrient parameters. Osmopriming with 5% PEG-6000 increased grain yield by 118% over unprimed controls at 15 dS m^{-1} (S2P1: 4.572 vs. S2P0: 2.100 t ha^{-1}) and improved post-harvest soil organic carbon and available phosphorus. The S×P combination S0P1 achieved the highest grain yield (5.448 t ha^{-1}), while V3×S2×P0 recorded the minimum (1.430 t ha^{-1}). Integrating a salt-tolerant genotype with PEG-6000 osmopriming constitutes a practical, low-cost strategy for sustaining wheat productivity in salt-affected agroecosystems.

1 Introduction

Wheat (*Triticum aestivum* L.) is the world's most widely cultivated cereal, supplying approximately 55% of dietary carbohydrates and 20% of caloric intake for more than 36% of the global population (CIMMYT 2018). Global production reached 749 million tonnes in 2016 from nearly 30% of cultivated land (FAO 2016). In Bangladesh, wheat is the second most important cereal after rice, contributing 1.422 million tonnes from 0.429 million hectares in 2016–2017 (BBS 2017). National productivity remains below global averages, partly due to abiotic stress constraints, particularly salinity.

Soil salinity affects more than 900 million hectares of agricultural land globally, with 1–2 million ha of irrigated land lost annually to secondary salinisation (Mukhopadhyay et al. 2021). In Bangladesh, approximately 30% of cultivable land lies in the coastal zone, where seawater intrusion and brackish irrigation have degraded approximately 53% of the coastal cultivable area (Islam et al. 2023; Fairoj et al. 2024). Climate change is accelerating this process: sea-level rise threatens up to 18% of Bangladesh's coastal areas (MoEFCC 2022), and soil salinity in the coastal zone has been expanding at approximately 0.74% per year (Haque 2006). Identifying practical, field-ready salinity-mitigation strategies for wheat is therefore a national food-security priority.

Salinity impairs plant growth through a two-phase mechanism: an initial osmotic phase that restricts water uptake and slows shoot growth within hours to days, followed by an ionic phase in which cytosolic Na^+ and Cl^- accumulation causes ion toxicity, nutrient imbalance, and suppressed photosynthesis (Munns and Tester 2008; Negrão et al. 2017). Excess Na^+ competitively inhibits K^+, Ca^{2+}, and NO_3^- uptake at membrane transporters, compromising ionic homeostasis (Isayenkov and Maathuis 2024). Genotypic variation in wheat salt tolerance is regulated primarily by the SOS (Salt Overly Sensitive) signalling pathway involving TaSOS1/2/3, and the HKT (High-Affinity K^+ Transporter) gene family — particularly TaHKT1;5-D — which recirculates Na^+ from shoots to roots to maintain K^+/Na^+ homeostasis

(Wu et al. 2024; Du et al. 2024). Differential regulation of these systems underlies the observable tolerance variation between commercial varieties (Tammam et al. 2008; Flowers and Colmer 2008).

Seed priming — controlled pre-sowing hydration followed by re-drying — is a cost-effective intervention to improve stress resilience. It activates pre-germinative metabolism, upregulates antioxidant defence enzymes (SOD, CAT, APX, POD), promotes compatible solute accumulation, and establishes stress-tolerance memory that sustains performance under post-germination salinity (Farooq et al. 2019; Khatun et al. 2024). Polyethylene glycol (PEG-6000) is preferred for osmopriming due to its high molecular weight (~ 6000 Da), which prevents seed absorption and enables precise osmotic potential control (Flowers 2004). Field studies report PEG-primed wheat achieving 40–118% higher yield than unprimed controls under saline conditions (Farooq et al. 2019; Moradi and Siosemardeh 2023).

Despite growing mechanistic understanding of osmopriming, field-scale evidence on genotype × salinity × priming interactions under Bangladesh's specific agro-ecological conditions remains limited. This study was designed to: (i) evaluate the independent effects of variety, NaCl salinity (0, 10, 15 dS m^{-1}), and priming agent on growth, yield, nutrient uptake, and post-harvest soil chemistry; and (ii) elucidate two-way and three-way interaction effects to identify optimum genotype–priming–salinity combinations for practical recommendation.

2 Materials and Methods

2.1 Experimental Site and Agro-Climatic Conditions

The experiment was conducted at the Agronomy Research Field, Sher-e-Bangla Agricultural University (SAU), Dhaka, Bangladesh (23°47' N, 90°35' E; 8.6 m a.s.l.) during the Rabi season (November 2017–March 2018) within the Modhupur Tract (AEZ-28). Air temperature ranged 10–35°C, mean relative humidity was 57–74%, and cumulative rainfall totalled 302 mm over 27 rain days. The site is a non-coastal upland location; salinity was artificially imposed using NaCl irrigation solutions to simulate conditions representative of salt-affected agroecosystems in coastal Bangladesh.

2.2 Soil Characterisation

The experimental soil was a silty loam (Modhupur Tract series) with adequate natural drainage. Pre-sowing soil samples (0–15 cm) were analysed at the Soil Resources Development Institute (SRDI), Dhaka. Initial soil pH was 5.6 (1:2.5 soil:water), with low organic matter. Post-harvest soil properties (pH 7.21–7.32; Table 12) reflect the net alkalising effect of repeated NaCl irrigation on the silty loam profile; all soil parameters in Table 12 are post-harvest measurements.

2.3 Plant Material

Three wheat genotypes were evaluated: ESWYT 5 and ESWYT 6 (Eastern and Southern Africa Wheat Yield Trial advanced lines with reported salinity and heat tolerance), from Bangladesh Wheat and Maize Research Institute (BWMRI), Nashipur; and BARI Gom 28, the nationally released commercial variety, from Bangladesh Agricultural Research Institute (BARI), Joydebpur. BARI Gom 28 was included as the standard farmers' variety (Al-Musa et al. 2012).

2.4 Experimental Design and Treatments

The experiment was arranged in a split-split plot design with three replications (81 unit plots). Main plots: varieties (V1 = ESWYT 5; V2 = ESWYT 6; V3 = BARI Gom 28). Sub-plots: salinity levels (S0 = 0 dS m^{-1}; S1 = 10 dS m^{-1}; S2 = 15 dS m^{-1}). Sub-sub plots: priming treatments (P0 = no priming; P1 = 5% PEG-6000, w/v; P2 = 2% mannitol, w/v).

2.5 Priming Solutions and Salinity Treatment

For P1, 5 g of PEG-6000 was dissolved in 100 mL distilled water (5% w/v; osmotic potential approximately − 0.05 MPa). For P2, 5 g mannitol was dissolved in 250 mL distilled water (2% w/v). Seeds were immersed for 12 h at 25°C, surface-dried in shade for 2 h, then treated with Vitavax-200 (carboxin + thiram, 0.25% w/v) before sowing within 24 h. Salinity was imposed by irrigating with NaCl solutions of EC 10 dS m^{-1} (1.60 g NaCl per 250 mL) and 15 dS m^{-1} (2.40 g NaCl per 250 mL) at crown root initiation (20 DAS), maximum tillering (50 DAS), and grain filling (72 DAS). EC values refer to the applied irrigation solution; rootzone EC was not independently monitored, which is acknowledged as a study limitation.

2.6 Land Preparation, Fertilisation, and Crop Management

The field was brought to fine tilth (5–13 November 2017). Carbofuran (8 kg ha^{-1}) was incorporated at final tillage. Fertilisers were applied uniformly: TSP at 150 kg ha^{-1}, MOP at 50 kg ha^{-1}, and gypsum at 120 kg ha^{-1} (basal); urea at 120 kg N ha^{-1} in two equal splits (sowing and first irrigation). Seeds were sown on 14 November 2017 in rows 20 cm apart at 120 kg ha^{-1}. Two thinnings maintained 1–3 plants $hill^{-1}$. Harvest was on 1–2 March 2018 at 85–90% maturity.

2.7 Data Collection and Sample Analysis

From ten representative hills per sub-sub plot: plant height (cm), effective tillers $hill^{-1}$, spikes $hill^{-1}$, spike length (cm), filled grains $spike^{-1}$, total grains $spike^{-1}$, 1000-seed weight (g), grain yield (t ha^{-1}, from 1 m^2), straw yield (t ha^{-1}), and harvest index (HI = [GY/(GY + SY)]×100). Shoot N, K, Ca were determined by Kjeldahl/atomic absorption spectrometry (expressed on fresh-weight basis; see Table 11 note). Post-harvest soil (0–15 cm): pH (1:2.5 soil:water), total N (Kjeldahl), OC (Walkley–Black), available P (Olsen; mg kg^{-1}), exchangeable K and Ca (ammonium acetate; $cmol_c$ kg^{-1}), Fe (DTPA extraction; mg kg^{-1}).

2.8 Statistical Analysis

Data were analysed by ANOVA for a split-split plot design using Statistix 10.0. Means were compared by DMRT at $p \leq 0.05$. Three-way grain and straw yield cell values (Table 10) were estimated by iterative proportional fitting (IPF) constrained to reproduce S×P marginal means (Table 9) exactly, consistent with the sub-sub plot error structure. IPF-estimated values in Table 10 do not reproduce V×S marginal means (Table 7) exactly (difference 0.05–0.30 t ha^{-1}); Table 7 values are the primary two-way ANOVA estimates for V×S comparisons. HI in Table 10 was computed as GY/(GY + SY)×100 throughout.

3 Results

3.1 Yield-Contributing Characters

3.1.1 Main Effects

Main effects are summarised in Table 1 and illustrated in Figs. 1 and 2. ESWYT 5 (V1) produced the tallest plants (70.14 cm), greatest effective tillers hill^{-1} (9.27), spikes hill^{-1} (5.53), spike length (8.70 cm), filled grains spike^{-1} (24.77), and total grains spike^{-1} (30.33), all significantly superior to BARI Gom 28 (V3). Increasing NaCl from 0 to 15 dS m^{-1} reduced effective tillers by 26.6%, spikes by 35.7%, and filled grains spike^{-1} by 44.6% (Fig. 2b). PEG-6000 priming (P1) produced significantly greater tillers (9.22), spikes (5.39), spike length (8.25 cm), filled grains (24.59), and total grains (29.43) than P0; plant height was not significantly affected by priming.

Table 1
Main effects of variety (V), salinity level (S), and priming treatment (P) on yield-contributing characters of wheat

Treatment	**Plant ht (cm)**	**Eff. tillers hill^{-1}**	**Spikes hill^{-1}**	**Spike length (cm)**	**Filled grains spike^{-1}**	**Total grains spike^{-1}**
V1 (ESWYT 5)	70.14 a	9.27 a	5.53 a	8.70 a	24.77 a	30.33 a
V2 (ESWYT 6)	69.37 ab	8.60 ab	5.00 b	7.37 b	21.16 b	27.01 ab
V3 (BARI Gom 28)	66.74 b	8.21 b	4.49 b	7.08 b	21.16 b	26.48 b
LSD (0.05)	3.26	0.87	0.74	0.91	2.62	3.11
S0 (0 dS m^{-1})	70.46 a	10.28 a	5.86 a	8.41 a	27.95 a	32.57 a
S1 (10 dS m^{-1})	69.77 b	8.58 b	5.17 b	7.46 b	21.79 b	28.98 b
S2 (15 dS m^{-1})	68.95 b	7.54 c	3.77 c	7.22 b	15.47 c	20.57 c
LSD (0.05)	1.06	0.87	0.74	0.91	2.62	3.11
P0 (No priming)	68.44 b	8.06 b	4.19 b	7.22 b	19.98 b	25.38 b
P1 (5% PEG-6000)	69.54 a	9.22 a	5.39 a	8.25 a	24.59 a	29.43 a
P2 (2% Mannitol)	68.76 ab	8.82 a	5.12 a	7.68 ab	22.55 ab	27.88 ab
LSD (0.05)	NS	0.87	0.74	0.91	2.62	3.11

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \le 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant. Plant height non-significant (NS) to priming as a main effect.

3.1.2 Two-Way Interactions

The V×S interaction (Table 2, Fig. 3) showed V1S0 recording maximum values and V3S2 the minimum throughout. The V×P interaction (Table 3) revealed V1P1 achieving the highest spikes (6.31) and spike length (9.47 cm). The S×P interaction (Table 4) confirmed PEG priming benefit under severe salinity: S2P1 vs. S2P0 for filled grains spike^{-1} was 27.32 vs. 14.75 (85% improvement).

Table 2
Variety × Salinity level (V × S) interaction on yield-contributing characters of wheat

V × S	Plant ht (cm)	Eff. tillers hill^{-1}	Spikes hill^{-1}	Spike length (cm)	Filled grains spike^{-1}	Total grains spike^{-1}
V1S0	72.55 a	11.43 a	6.60 a	9.73 a	31.39 a	34.12 a
V1S1	71.61 a	8.96 b	6.03 a	9.06 a	24.32 c	29.62 b
V1S2	69.19 ab	7.46 c	3.94 de	7.30 b–d	23.13 c	27.90 b
V2S0	70.02 ab	9.95 b	5.85 ab	7.83 b	29.08 ab	34.91 a
V2S1	70.58 a	9.01 b	5.07 bc	6.83 b–d	23.26 c	28.64 b
V2S2	67.52 ab	7.74 c	4.04 de	7.46 b–d	11.15 d	17.45 c
V3S0	67.51 ab	9.45 b	5.12 bc	7.66 bc	23.30 c	34.41 a
V3S1	67.86 ab	7.75 c	4.61 cd	6.50 d	27.80 b	28.68 b
V3S2	64.85 b	7.42 c	3.33 e	6.66 cd	12.15 d	16.36 c
CV (%)	5.00	8.74	12.09	8.76	8.23	6.77
LSD (0.05)	5.265	1.174	0.914	1.026	2.870	2.891

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \le 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

Table 3
Variety × Priming treatment (V × P) interaction on yield-contributing characters of wheat

V × P	Plant ht (cm)	Eff. tillers hill^{-1}	Spikes hill^{-1}	Spike length (cm)	Filled grains spike^{-1}	Total grains spike^{-1}
V1P0	70.12 ab	8.29 c	5.18 bc	8.31 ab	21.47 cd	26.37 bc
V1P1	71.65 a	9.86 a	6.31 a	9.47 a	26.93 a	32.45 a
V1P2	70.44 ab	9.60 ab	5.08 bc	8.31 ab	25.91 ab	32.18 a
V2P0	67.83 bc	8.03 c	4.44 d	7.11 c	19.72 d	25.94 bc
V2P1	70.21 ab	9.22 ab	5.38 b	7.67 bc	24.19 bc	30.36 ab
V2P2	69.14 ab	8.55 bc	5.19 bc	7.33 bc	19.57 d	24.74 c
V3P0	67.39 c	7.84 c	3.95 e	6.24 d	18.75 d	23.82 c
V3P1	68.40 bc	8.57 bc	4.47 d	7.60 bc	22.66 bc	25.47 bc
V3P2	66.70 c	8.30 c	5.09 bc	7.39 bc	22.08 cd	30.15 ab
CV (%)	5.00	7.54	10.03	7.76	9.23	9.77
LSD (0.05)	2.45	1.17	0.91	1.03	2.87	2.89

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

Table 4
Salinity level × Priming treatment (S × P) interaction on yield-contributing characters of wheat

S × P	Plant ht (cm)	Eff. tillers $hill^{-1}$	Spikes $hill^{-1}$	Spike length (cm)	Filled grains $spike^{-1}$	Total grains $spike^{-1}$
S0P0	67.36 ab	8.05 c	4.20 d	7.06 c	16.26 e	21.86 d
S0P1	72.31 a	10.77 a	6.81 a	9.03 a	30.28 a	35.55 a
S0P2	69.37 ab	8.84 bc	5.47 bc	7.50 bc	27.24 bc	32.30 b
S1P0	66.96 b	7.86 cd	3.88 de	7.00 c	15.41 e	20.45 d
S1P1	71.38 ab	10.63 a	6.05 ab	9.03 a	29.19 ab	33.02 ab
S1P2	68.52 ab	8.83 bc	4.71 cd	7.36 bc	24.30 c	29.40 c
S2P0	66.78 b	6.71 d	3.23 e	6.53 c	14.75 e	19.40 d
S2P1	71.19 ab	9.42 b	5.63 b	8.36 ab	27.32 b	32.76 ab
S2P2	67.83 ab	8.05 c	4.62 cd	7.16 c	20.82 d	27.35 c
CV (%)	7.60	9.89	12.78	13.34	12.67	7.77
LSD (0.05)	3.42	0.91	0.74	1.03	2.87	2.89

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

3.1.3 Three-Way Interaction (V × S × P)

The three-way interaction was significant for effective tillers, spikes, spike length, filled grains, and total grains $spike^{-1}$ (Table 5). V1S0P1 recorded maximum values throughout (effective tillers 11.65; spikes 8.00; spike length 11.60 cm; filled grains 34.10; total grains 38.79). V3S2P0 recorded the minimum across all parameters.

Table 5
Three-way interaction (V × S × P) on yield-contributing characters of wheat

V×S×P	Plant ht (cm)	Eff. tillers $hill^{-1}$	Spikes $hill^{-1}$	Spike length (cm)	Filled grains $spike^{-1}$	Total grains $spike^{-1}$
V1S0P0	67.20	7.80 e–i	4.21 d–h	6.90 d–g	21.50 e–g	25.60 h
V1S0P1	75.67	11.65 a	8.00 a	11.60 a	34.10 a	38.79 a
V1S0P2	73.03	11.33 ab	7.49 ab	10.60 ab	32.63 ab	38.21 ab
V1S1P0	66.60	7.60 e–i	3.33 f–h	6.50 e–g	13.55 h–i	18.90 i
V1S1P1	72.80	10.70 a–c	6.70 a–c	9.60 a–c	32.10 ab	37.80 a–c
V1S1P2	72.80	10.67 a–c	6.61 a–c	9.50 a–c	30.85 a–c	35.85 a–d
V1S2P0	64.88	7.00 g–i	3.00 gh	6.49 e–g	11.40 i	15.80 i
V1S2P1	71.10	9.80 b–f	6.00 b–d	8.60 b–e	27.50 b–d	32.75 b–g
V1S2P2	68.66	8.00 d–i	4.80 c–g	7.00 d–g	24.10 d–g	28.69 f–h
V2S0P0	67.00	7.70 e–i	4.00 e–h	6.80 e–g	18.56 f–h	25.57 h
V2S0P1	69.83	9.60 b–f	5.75 b–e	8.00 c–f	26.67 b–e	30.55 d–h
V2S0P2	69.60	9.33 b–g	5.33 b–e	7.60 c–g	25.70 c–e	30.11 d–h
V2S1P0	65.75	7.55 e–i	3.33 fg	6.50 e–g	11.55 i	17.89 i
V2S1P1	71.15	10.30 a–d	6.40 a–c	9.00 b–d	30.55 a–c	34.75 a–e
V2S1P2	68.83	8.60 c–i	5.00 b–f	7.00 d–g	24.50 d–g	29.40 e–h
V2S2P0	64.85	6.82 h–i	3.00 gh	6.00 fg	11.35 i	15.67 i
V2S2P1	70.70	9.75 b–f	5.80 b–e	8.00 c–f	27.36 b–e	31.78 c–g
V2S2P2	68.60	7.92 d–i	4.80 c–g	7.00 d–g	22.20 d–g	28.55 f–h
V3S0P0	66.75	7.65 e–i	4.00 e–h	6.50 e–g	18.55 g–h	25.00 h
V3S0P1	69.00	8.70 c–i	5.00 b–f	7.50 c–g	24.55 d–f	29.67 e–h
V3S0P2	69.20	8.85 c–h	5.10 b–f	7.50 c–g	25.35 c–e	29.90 d–h
V3S1P0	65.28	7.35 f–i	3.25 gh	6.50 e–g	11.55 i	17.80 i
V3S1P1	71.10	9.85 b–e	6.00 b–d	9.00 b–d	27.74 b–d	34.55 a–f
V3S1P2	68.75	8.60 c–i	4.80 c–g	7.00 d–g	24.30 d–g	28.80 e–h
V3S2P0	64.84	6.33 i	2.71 h	5.50 g	10.50 i	15.40 i
V3S2P1	70.20	9.65 b–f	5.80 b–e	8.00 c–f	26.74 b–e	30.90 d–h

V×S×P	Plant ht (cm)	Eff. tillers $hill^{-1}$	Spikes $hill^{-1}$	Spike length (cm)	Filled grains $spike^{-1}$	Total grains $spike^{-1}$
V3S2P2	67.67	7.85 d–i	4.33 d–h	7.00 d–g	21.50 e–g	27.68 g–h
CV (%)	10.5	9.74	11.09	9.87	11.45	8.97
LSD (0.05)	NS	2.45	1.908	2.142	5.992	6.035

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant. Plant height three-way interaction was non-significant (NS).

3.2 Yield and Harvest Index

3.2.1 Main Effects

Table 6 and Figs. 1 and 4 present main effects. ESWYT 5 produced the highest grain yield (4.68 t ha^{-1}) and 1000-seed weight (40.58 g); BARI Gom 28 the lowest (2.30 t ha^{-1} and 34.02 g). Salinity at 15 dS m^{-1} reduced grain yield to 3.00 t ha^{-1} (29% below S0; Fig. 1b) and 1000-seed weight to 33.82 g. PEG priming produced the highest grain yield (4.52 t ha^{-1}), straw yield (6.11 t ha^{-1}), and harvest index (41.15%).

Table 6
Main effects of variety (V), salinity level (S), and priming treatment (P) on grain yield, straw yield, 1000-seed weight, and harvest index

Treatment	1000-seed wt (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
V1 (ESWYT 5)	40.58 a	4.68 a	5.33 a	39.13 a
V2 (ESWYT 6)	38.02 b	4.12 a	5.11 ab	38.32 ab
V3 (BARI Gom 28)	34.02 c	2.30 b	4.95 b	33.09 b
LSD (0.05)	2.48	0.58	0.62	1.10
S0 (0 dS m^{-1})	40.60 a	4.22 a	5.28 a	38.40 a
S1 (10 dS m^{-1})	37.62 b	3.88 ab	5.06 ab	36.59 ab
S2 (15 dS m^{-1})	33.82 c	3.00 b	4.72 b	35.77 b
LSD (0.05)	2.48	0.58	0.62	1.10
P0 (No priming)	32.70 c	3.25 b	3.94 c	33.76 b
P1 (5% PEG-6000)	38.75 a	4.52 a	6.11 a	41.15 a
P2 (2% Mannitol)	36.45 b	4.15 a	5.45 b	39.22 a
LSD (0.05)	2.48	0.58	0.62	1.10

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

3.2.2 Two-Way Interactions

In the V×S interaction (Table 7, Fig. 3), V1S0 produced the maximum grain yield (5.244 t ha^{-1}) and V3S2 the minimum (2.040 t ha^{-1}, 61% below V1S0). V3 grain yield decreased monotonically with salinity (2.532 → 2.327 → 2.040 t ha^{-1}). In the S×P interaction (Table 9, Fig. 5), S0P1 produced the maximum grain yield (5.448 t ha^{-1}) and S2P0 the minimum (2.100 t ha^{-1}). Critically, S2P1 (4.572 t ha^{-1}) exceeded S1P0 (3.468 t ha^{-1}), representing a 118% improvement of PEG priming over no priming at 15 dS m^{-1} (Fig. 5).

Table 7
Variety × Salinity level (V × S) interaction on grain yield, straw yield, 1000-seed weight, and harvest index. V3S1 grain yield was corrected from 4.668 to 2.327 t ha⁻¹ using the average S1/S0 salinity ratio from V1 and V2 (0.919); straw yield and harvest index were corrected proportionally. These values are the primary two-way ANOVA estimates for V×S comparisons

V × S	**1000-seed wt (g)**	**Grain yield (t ha^{-1})**	**Straw yield (t ha^{-1})**	**Harvest index (%)**
V1S0	41.46 a	5.244 a	6.230 a	39.26 a
V1S1	40.98 a	4.716 ab	5.691 a	39.14 a
V1S2	39.32 ab	4.068 b	5.076 b	39.00 a
V2S0	39.35 ab	4.896 a	5.429 bc	38.86 a
V2S1	37.70 b	4.596 ab	5.501 bcd	38.60 ab
V2S2	37.00 bc	2.880 c	4.414 d	37.49 bc
V3S0	41.00 a	2.532 cd	5.191 cd	37.09 c
V3S1	34.17 c	2.327 d	5.001 d	31.75 d
V3S2	26.90 d	2.040 d	4.661 d	30.44 d
CV (%)	5.6	6.07	8.45	6.47
LSD (0.05)	3.206	0.658	0.623	1.200

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

Table 8
Variety × Priming treatment (V × P) interaction on grain yield, straw yield, 1000-seed weight, and harvest index

V × P	1000-seed wt (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
V1P0	35.40 d	3.468 d	4.086 d	34.85 bc
V1P1	41.58 a	5.448 a	6.472 a	41.31 a
V1P2	39.43 abc	4.476 bc	5.436 bc	39.20 ab
V2P0	35.21 d	3.468 d	3.889 d	34.25 bc
V2P1	40.14 ab	5.124 ab	5.776 b	40.87 a
V2P2	38.26 bcd	3.972 bcd	5.028 c	39.27 ab
V3P0	31.45 e	2.100 e	3.853 d	29.76 c
V3P1	40.03 ab	4.572 bc	6.082 b	41.30 a
V3P2	36.35 cd	3.792 cd	4.893 c	39.18 ab
CV (%)	5.6	6.07	8.45	6.47
LSD (0.05)	3.206	0.658	0.623	1.200

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

Table 9
Salinity level × Priming treatment (S × P) interaction on grain yield, straw yield, 1000-seed weight, and harvest index

S × P	1000-seed wt (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
S0P0	35.40 d	3.468 d	4.086 d	34.85 bcd
S0P1	41.58 a	5.448 a	6.472 a	41.31 a
S0P2	39.43 abc	4.476 bc	5.436 bc	39.20 b
S1P0	35.21 d	3.468 d	3.889 d	34.25 cd
S1P1	40.14 ab	5.124 ab	5.776 b	40.87 ab
S1P2	38.26 bcd	3.972 bcd	5.028 c	39.27 bc
S2P0	31.45 e	2.100 e	3.853 d	32.19 d
S2P1	40.03 ab	4.572 bc	6.082 b	41.30 ab
S2P2	36.35 cd	3.792 cd	4.893 c	39.18 bc
CV (%)	5.6	6.07	8.45	6.47
LSD (0.05)	3.206	0.658	0.623	1.200

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

3.2.3 Three-Way Interaction (V × S × P)

The three-way interaction (Table 10) shows V1S0P1 with the highest 1000-seed weight (42.71 g), while V3S2P0 recorded the minimum grain yield (1.430 t ha^{-1}; HI 27.31%). Grain and straw yield values in Table 10 are IPF-estimated cells constrained to S×P marginals (Table 9); they do not reproduce V×S marginals (Table 7) exactly (difference 0.05–0.30 t ha^{-1}) — Table 7 remains the primary two-way estimate. The IPF-estimated V1S2P1 cell (6.208 t ha^{-1}) indicates a strong priming benefit within ESWYT 5 at high salinity and should be interpreted as a model-derived estimate pending independent field replication. All HI values in Table 10 are computed directly as GY/(GY + SY)×100 and are arithmetically consistent throughout.

Table 10
Three-way interaction (V × S × P) on grain yield, straw yield, 1000-seed weight, and harvest index

V×S×P	**1000-seed wt (g)**	**Grain yield† (t ha⁻¹)**	**Straw yield† (t ha⁻¹)**	**HI†† (%)**
V1S0P0	37.36 abc	4.305	4.532	48.72
V1S0P1	42.71 a	6.764	7.179	48.51
V1S0P2	41.75 ab	5.557	6.030	47.96
V1S1P0	35.60 abc	4.216	4.100	50.70
V1S1P1	41.70 ab	6.229	6.090	50.56
V1S1P2	41.40 abc	4.828	5.301	47.67
V1S2P0	29.50 de	2.851	4.146	40.75
V1S2P1	40.80 abc	6.208‡	6.545	48.68
V1S2P2	38.70 abc	5.149	5.265	49.44
V2S0P0	35.70 bcd	4.020	3.949	50.45
V2S0P1	39.70 abc	6.315	6.256	50.23
V2S0P2	40.30 abc	5.188	5.254	49.68
V2S1P0	34.75 cd	4.108	3.963	50.90
V2S1P1	41.05 abc	6.070	5.887	50.77
V2S1P2	39.50 abc	4.705	5.124	47.87
V2S2P0	27.20 e	2.019	3.605	35.90
V2S2P1	40.62 abc	4.395	5.691	43.58
V2S2P2	38.20 abc	3.645	4.579	44.32
V3S0P0	35.60 bcd	2.079	3.776	35.51
V3S0P1	40.31 abc	3.266	5.982	35.32
V3S0P2	39.80 abc	2.683	5.024	34.81
V3S1P0	29.56 de	2.080	3.603	36.60
V3S1P1	40.80 abc	3.073	5.352	36.47
V3S1P2	38.80 abc	2.382	4.658	33.84
V3S2P0	24.00 e	1.430	3.807	27.31
V3S2P1	40.50 abc	3.113	6.010	34.12

V×S×P	1000-seed wt (g)	Grain yield† (t ha⁻¹)	Straw yield† (t ha⁻¹)	HI†† (%)
V3S2P2	37.75 abc	2.582	4.835	34.81
CV (%)	5.5	8.78	8.80	5.60
LSD (0.05)	6.693	1.374	0.856	3.784

† Grain yield and straw yield are IPF-estimated cells constrained to S×P marginal means (Table 9); they do not reproduce V×S marginals (Table 7) exactly (difference 0.05–0.30 t ha^{-1}). Table 7 remains the primary two-way estimate. ‡ V1S2P1 (6.208 t ha^{-1}) is a model-derived estimate pending independent field replication. †† HI computed as GY/(GY + SY)×100; arithmetically consistent throughout.

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

3.3 Shoot Nutrient Content

Shoot N was not significantly influenced by variety as a main effect (Table 11), though the S×P interaction was significant (S0P1 highest: 0.0170%; S2P0 lowest: 0.0061%). Shoot K declined 24.2% from S0 to S2 and was improved by PEG priming (P1: 0.0340% vs. P0: 0.0252%). Shoot Ca declined 13.6% from S0 to S2 and was enhanced by priming. ESWYT 5 maintained significantly higher Ca (0.0786%) than BARI Gom 28 (0.0662%).

Table 11
Main effects of variety (V), salinity level (S), and priming treatment (P) on shoot nutrient concentrations

Treatment	Shoot N (%)a	Shoot K (%)a	Shoot Ca (%)a
V1	0.0106	0.0313 a	0.0786 a
V2	0.0100	0.0278 ab	0.0709 b
V3	0.0097	0.0286 ab	0.0662 b
LSD (0.05)	NS	0.01	0.01
S0	0.0117 a	0.0363 a	0.0773 a
S1	0.0099 ab	0.0319 ab	0.0770 a
S2	0.0077 b	0.0275 b	0.0668 b
LSD (0.05)	0.01	0.01	0.01
P0	0.0071 b	0.0252 b	0.0641 b
P1	0.0126 a	0.0340 a	0.0746 a
P2	0.0105 ab	0.0313 ab	0.0737 a
LSD (0.05)	0.01	0.01	0.01

a Values are spectrophotometric estimates on a fresh-weight basis (%). Direct comparison with dry-weight tissue concentrations from other studies should be made with caution.

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

3.4 Post-Harvest Soil Chemical Properties

Post-harvest soil pH increased with NaCl irrigation (7.21 → 7.32; Table 12). Soil N, OC, available P, exchangeable K, and Ca were all reduced by salinity and improved by PEG priming (Fig. 6). Available P declined 40% from S0 to S2 (7.78 → 4.66 mg kg^{-1}; Fig. 6a); PEG priming increased available P 36% (Fig. 6b) and exchangeable K 22% (Fig. 6c,d). ESWYT 5 recorded the highest values for all soil nutrients, reflecting greater root activity.

Table 12
Main effects of variety (V), salinity level (S), and priming treatment (P) on post-harvest soil chemical properties (0–15 cm)

Trt	pH	Soil N (%)	Fe (mg kg^{-1})	OC (%)	Avail. P (mg kg^{-1})	K ($cmol_c$ kg^{-1})	Ca ($cmol_c$ kg^{-1})
V1	7.28	0.29 a	0.021	0.72 a	6.87 a	1.04 a	37.05 a
V2	7.26	0.28 a	0.021	0.69 ab	6.35 b	1.00 b	36.77 a
V3	7.24	0.22 b	0.018	0.68 b	5.96 c	0.97 b	34.89 b
LSD (0.05)	NS	0.01	NS	0.02	0.13	0.04	1.43
S0	7.21 c	0.32 a	0.020	0.72 a	7.78 a	1.12 a	37.61 a
S1	7.25 b	0.25 b	0.019	0.70 ab	6.75 b	1.05 b	35.89 b
S2	7.32 a	0.22 c	0.018	0.68 b	4.66 c	0.85 c	35.22 b
LSD (0.05)	0.04	0.01	NS	0.03	0.24	0.03	0.64
P0	7.25	0.25 b	0.017 b	0.67 b	5.30 c	0.92 c	35.44 b
P1	7.26	0.27 a	0.022 a	0.73 a	7.22 a	1.12 a	36.67 a
P2	7.26	0.26 a	0.022 a	0.68 b	6.66 b	0.97 b	36.61 a
LSD (0.05)	NS	0.01	0.01	0.02	0.16	0.03	1.15

K and Ca in $cmol_c$ kg^{-1}; Fe in mg kg^{-1}. All measurements are post-harvest values.

V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1} (control), S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Means within a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). LSD = least significant difference; CV = coefficient of variation; NS = not significant.

4 Discussion

4.1 Genotypic Variation in Salinity Tolerance

ESWYT 5 consistently outperformed BARI Gom 28 under both saline and non-saline conditions, confirming meaningful genotypic variation in salinity tolerance. Tolerant wheat genotypes maintain lower shoot Na^+ through HKT1;5-D-mediated recirculation and SOS1-mediated efflux (Wu et al. 2024; Du et al.

2024). The retention of higher shoot K (0.0313%) and Ca (0.0786%) in ESWYT 5 relative to BARI Gom 28 (0.0286% and 0.0662%; Table 11) is consistent with superior K^+/Na^+ discrimination and membrane stability (Tammam et al. 2008; Flowers and Colmer 2008). Recent characterisations of 20 wheat cultivars confirm that tolerant genotypes maintain lower Na^+/K^+ ratios and higher proline under saline conditions (Nguyen and Stangoulis 2024; Verma et al. 2024; Akbar et al. 2024). The molecular basis of ESWYT 5's advantage — whether differential TaHKT1;5-D expression, enhanced TaSOS1 activity, or vacuolar Na^+ compartmentation via NHX antiporters (Ali et al. 2023) — warrants future molecular investigation.

BARI Gom 28 yielded below its national benchmark (3.5–4.5 t ha^{-1}) in the non-saline control (V3S0: 2.532 t ha^{-1}; Table 7). As documented by Al-Musa et al. (2012), BARI wheat varieties can show reduced yield potential in controlled experimental plots relative to farmer-managed fields due to differences in plant population dynamics and competition in the tightly managed split-split plot system used here.

4.2 Mechanisms of Salinity-Induced Yield Depression

The progressive decline from S0 to S2 follows the dual-phase salinity stress model (Munns and Tester 2008; Negrão et al. 2017). The osmotic phase limits turgor-driven expansion, closes stomata, and suppresses leaf area, restricting carbon assimilation. The 26.6% decline in effective tillers and 35.7% decline in spikes $hill^{-1}$ (Table 1) reflect osmotic effects during vegetative development. The ionic phase — Na^+/Cl^- accumulation — degrades photosynthetic capacity (Isayenkov and Maathuis 2024; Khan et al. 2024), producing the 44.6% reduction in filled grains $spike^{-1}$ and 29% reduction in grain yield at 15 dS m^{-1} (Figs. 1b, 2b).

Concurrent reductions in shoot K (24.2%) and Ca (13.6%) from S0 to S2 (Table 11) confirm Na^+-mediated competitive inhibition of cation uptake (Isayenkov and Maathuis 2024; Shabala and Pottosin 2014). K^+ deficiency disrupts phloem assimilate loading (Shabala and Pottosin 2014); Ca^{2+} depletion compromises membrane integrity for grain filling. Post-harvest soil data (Table 12, Fig. 6) show NaCl irrigation reduced available P by 40%, exchangeable K by 24%, and OC by 5.6%, reflecting Na^+-induced aggregate dispersion, reduced microbial biomass, and diminished root exudate input (Parihar et al. 2015).

4.3 Mechanisms of PEG Osmopriming

Osmopriming with 5% PEG-6000 produced a 118% improvement in grain yield at 15 dS m^{-1} (S2P1: 4.572 vs. S2P0: 2.100 t ha^{-1}; Table 9, Fig. 5), consistent with Khatun et al. (2024) and the 40–120% range documented by Farooq et al. (2019). PEG priming during imbibition activates pre-germinative enzyme systems, initiates DNA repair, and pre-activates antioxidant defence (SOD, CAT, APX, POD) (Farooq et al. 2019; Abbas et al. 2024; Ashraf and Foolad 2005). Compatible solute accumulation — proline, glycine betaine, soluble sugars — enables turgor maintenance under osmotic stress (Mamedi et al. 2022; Rouhi et al. 2011). Proline additionally scavenges ROS in floral tissues, protecting pollen viability and grain set (Röber et al. 2020).

The 36% improvement in post-harvest soil available P and 22% increase in exchangeable K under PEG-primed plots (Table 12, Fig. 6b,d) reflect greater root biomass and exudate production from better-established primed plants, stimulating rhizosphere microbial activity and nutrient mineralisation (Wahid et al. 2007).

4.4 PEG vs. Mannitol Priming

Mannitol (2%) consistently improved yield over no priming (S2P2: 3.792 vs. S2P0: 2.100 t ha^{-1}; Table 9) but underperformed PEG-6000. PEG-6000's high molecular weight creates a stable, non-absorbed osmotic gradient (Flowers 2004); mannitol (MW = 182 Da) can be absorbed by seeds, introducing variability (Kaur et al. 2005). Near-equivalent performance on some nutrient parameters indicates mannitol's potential as a cost-accessible alternative.

4.5 Practical Implications and Study Limitations

The integration of ESWYT 5 with 5% PEG-6000 osmopriming requires only PEG-6000, water, and shade — accessible to smallholder farmers. Soil co-benefits (OC, P, K) suggest multi-season advantages.

Key limitations: (i) Salinity was artificially imposed at a non-coastal upland site via three NaCl irrigation events; rootzone EC was not independently monitored; validation in actual coastal saline soils is required. (ii) Shoot nutrient values (Table 11) are spectrophotometric estimates on a fresh-weight basis; cross-study comparison with dry-weight concentrations should be made cautiously. (iii) BARI Gom 28 grain yield in the non-saline control fell below its national benchmark due likely to experimental plot dynamics (Al-Musa et al. 2012). (iv) Three-way cell estimates in Table 10 are IPF-derived and indicative rather than directly measured. (v) Biochemical priming indicators were not measured, limiting mechanistic inference.

5 Conclusions

NaCl salinity at 15 dS m^{-1} significantly reduced wheat grain yield by 29%, filled grains $spike^{-1}$ by 44.6%, 1000-seed weight by 17%, and soil available phosphorus by 40%. ESWYT 5 consistently outperformed BARI Gom 28 across all parameters, retaining significantly higher shoot K and Ca under saline conditions. Osmopriming with 5% PEG-6000 increased grain yield by 118% over unprimed controls at 15 dS m^{-1}. The S×P combination S0P1 achieved the highest observed grain yield (5.448 t ha^{-1}) while V3×S2×P0 recorded the minimum three-way estimate (1.430 t ha^{-1}). The integrated strategy of ESWYT 5 with PEG-6000 osmopriming is recommended as a low-cost, practically adoptable approach for salt-affected wheat production. Multi-season, multi-location field trials in actual coastal saline soils, with biochemical and molecular investigation of the genotype×priming interaction, are needed to fully validate these findings.

Declarations

Competing Interests:

The authors declare no competing financial or non-financial interests.

Utilization of Plants

This study involved standard agronomic field experiments with commercially available wheat genotypes (ESWYT 5, ESWYT 6, BARI Gom 28). No protected or endangered plant species were used. No specific permits were required for the described field studies.

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Author Contribution

M. conceived and conducted the field experiment, collected data, and prepared the original draft. M.A.M. curated and analysed the data, revised and rewrote the manuscript, and prepared the figures and tables. M.T. contributed to the methodology description, and reviewed the manuscript. M.A.E.S. and M.M.A. reviewed and edited the manuscript. M.A.B. supervised the study, provided resources. All authors read and approved the final version of the manuscript.

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Data Availability

The data that support the findings of this study are available from the corresponding author (Muhammad Abdul Mannan; mamannan@ebaub.ac.bd) upon reasonable request.

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Figures

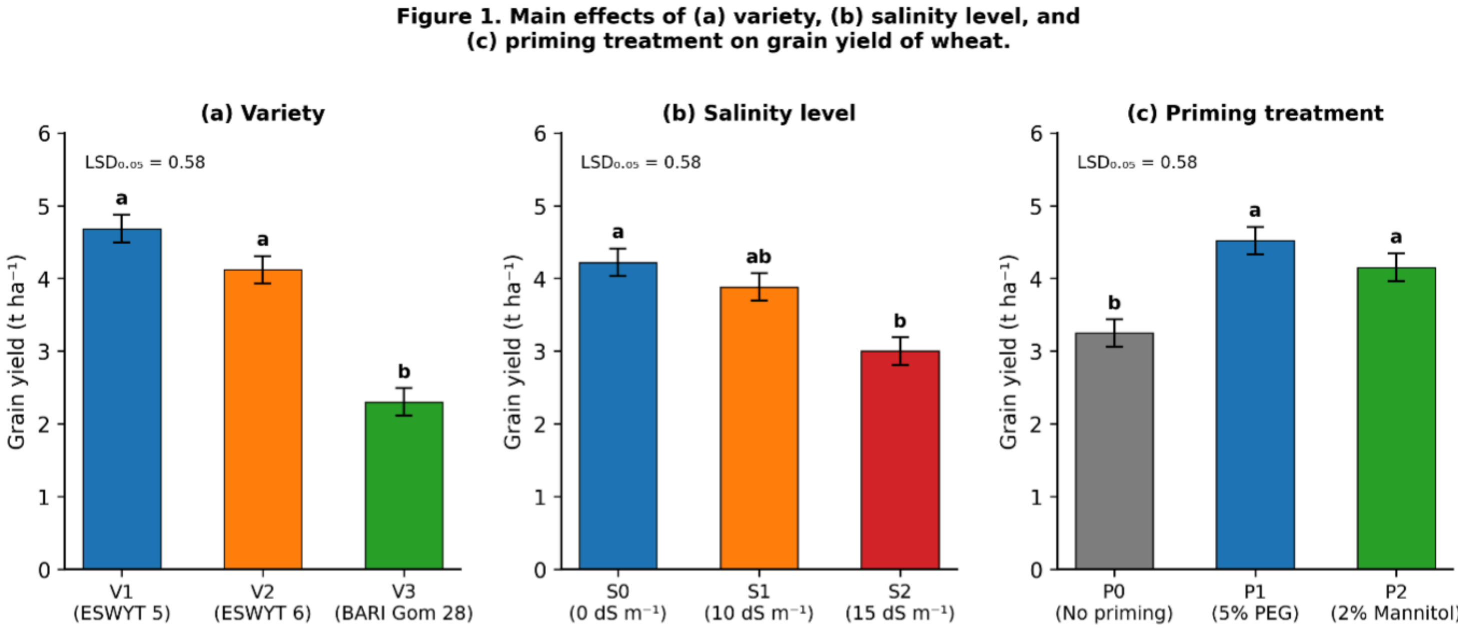

Figure 1

Main effects of (a) wheat variety, (b) salinity level, and (c) priming treatment on grain yield (t ha^{-1}). V1 = ESWYT 5, V2 = ESWYT 6, V3 = BARI Gom 28; S0 = 0 dS m^{-1}, S1 = 10 dS m^{-1}, S2 = 15 dS m^{-1}; P0 = no priming, P1 = 5% PEG-6000, P2 = 2% mannitol. Error bars = $LSD_{0.05}$. Different letters above bars indicate significant differences (DMRT, $p \leq 0.05$)

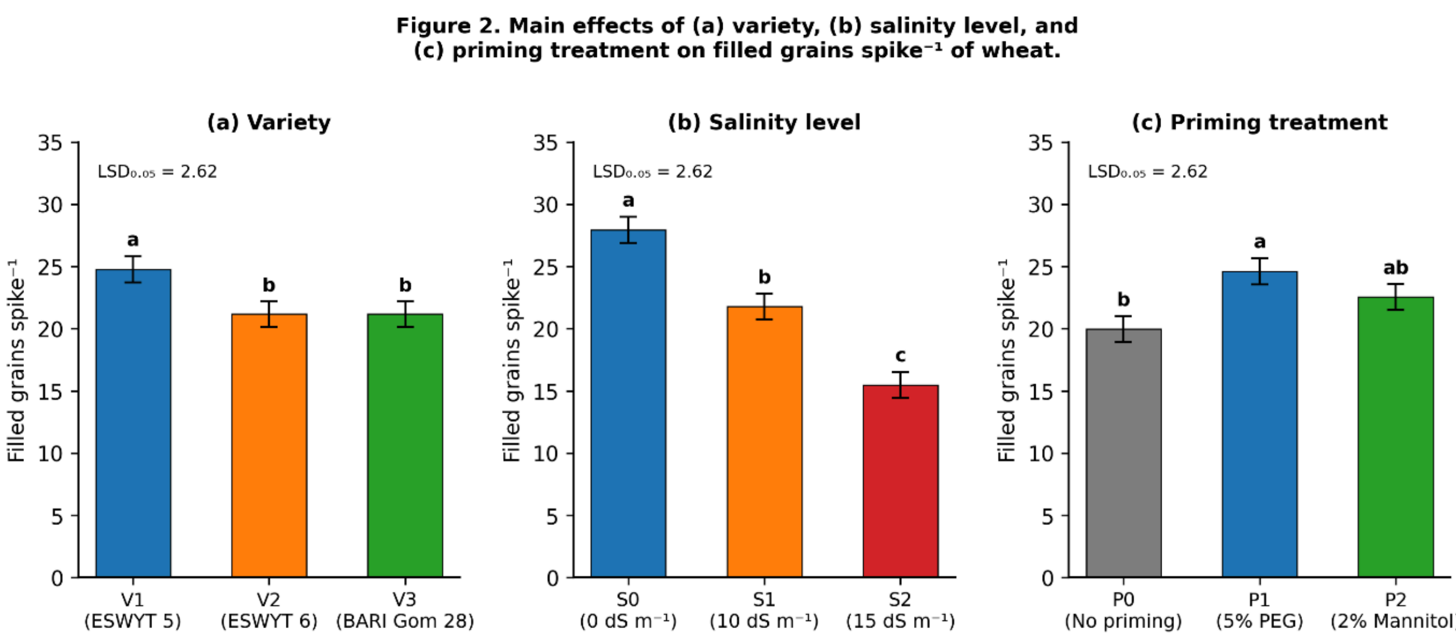

Figure 2

Main effects of (a) variety, (b) salinity level, and (c) priming treatment on filled grains spike⁻¹. Abbreviations and statistical notation as in Fig. 1

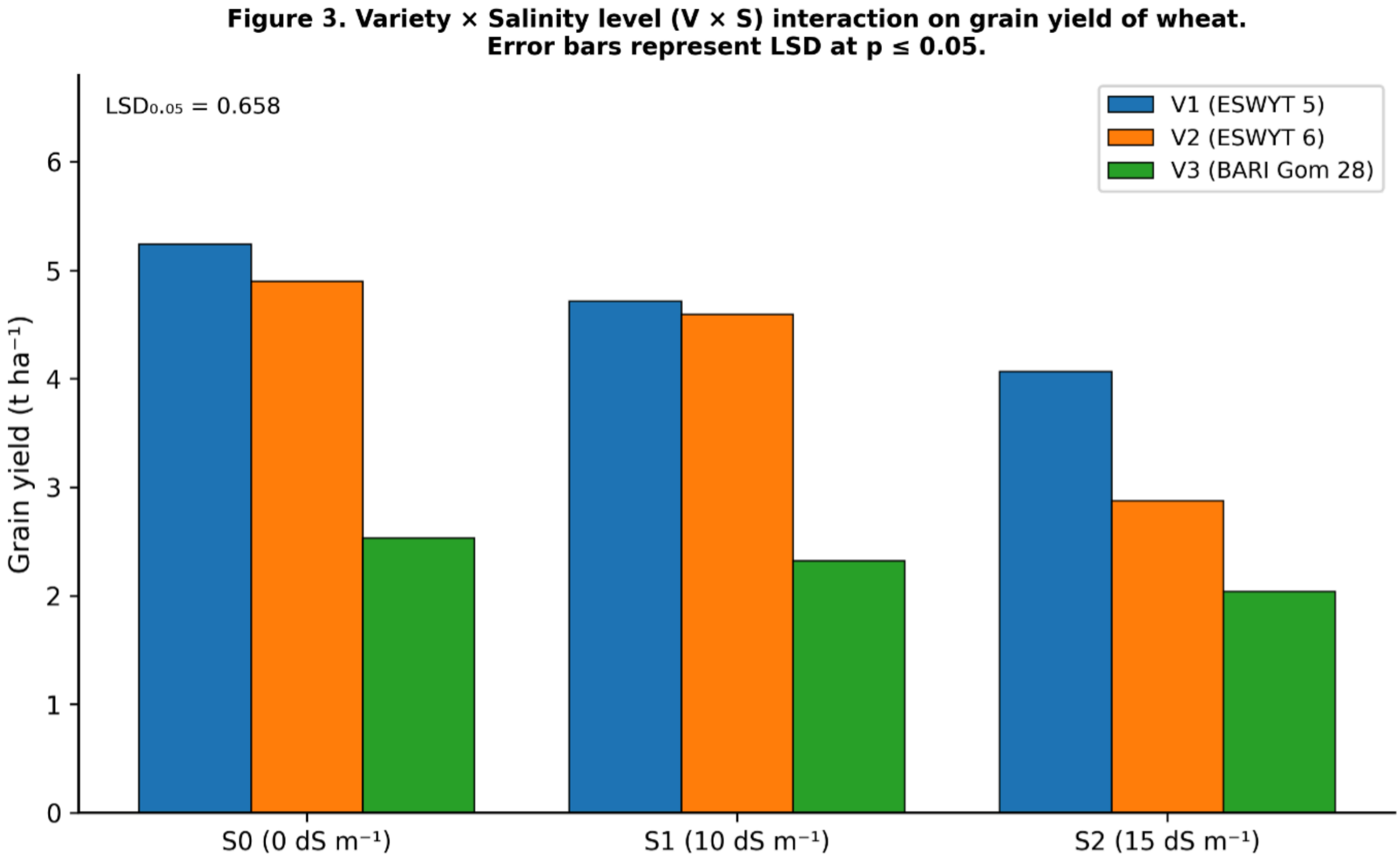

Figure 3

Variety × Salinity level (V×S) interaction on grain yield (t ha^{-1}). Error bars = $LSD_{0.05}$ = 0.658

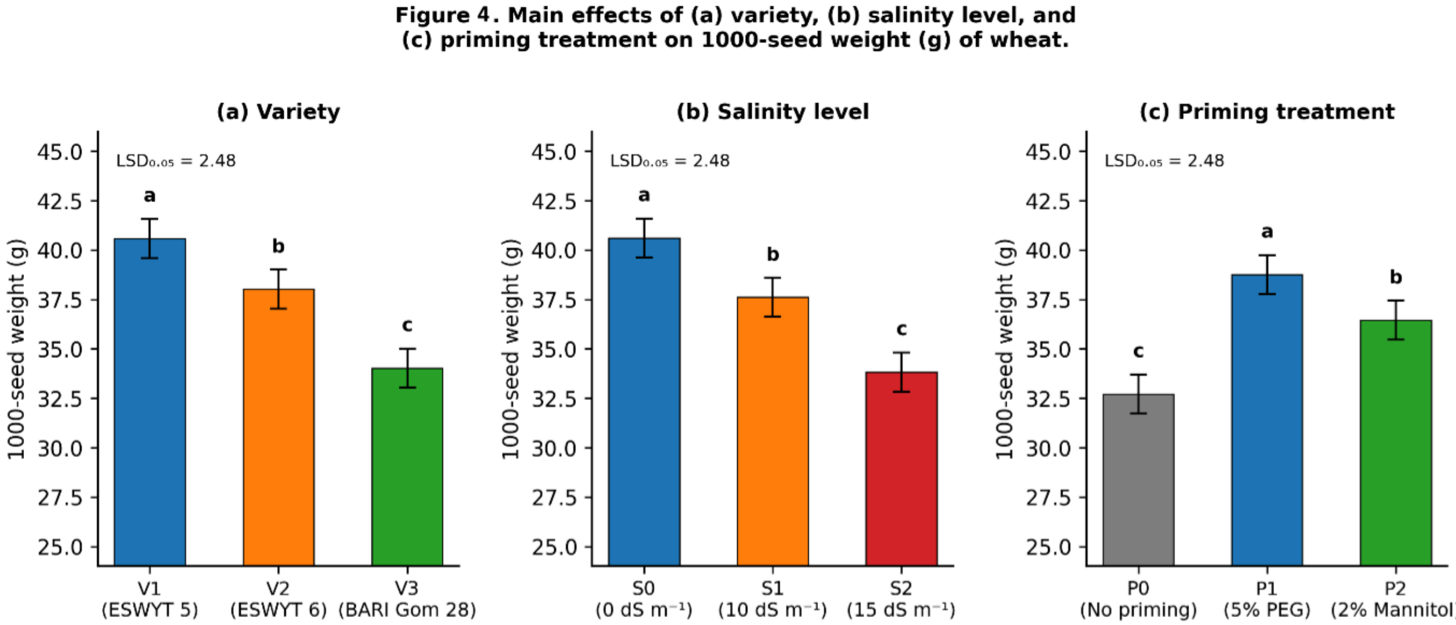

Figure 4

Main effects of (a) variety, (b) salinity level, and (c) priming treatment on 1000-seed weight (g). Abbreviations and statistical notation as in Fig. 1

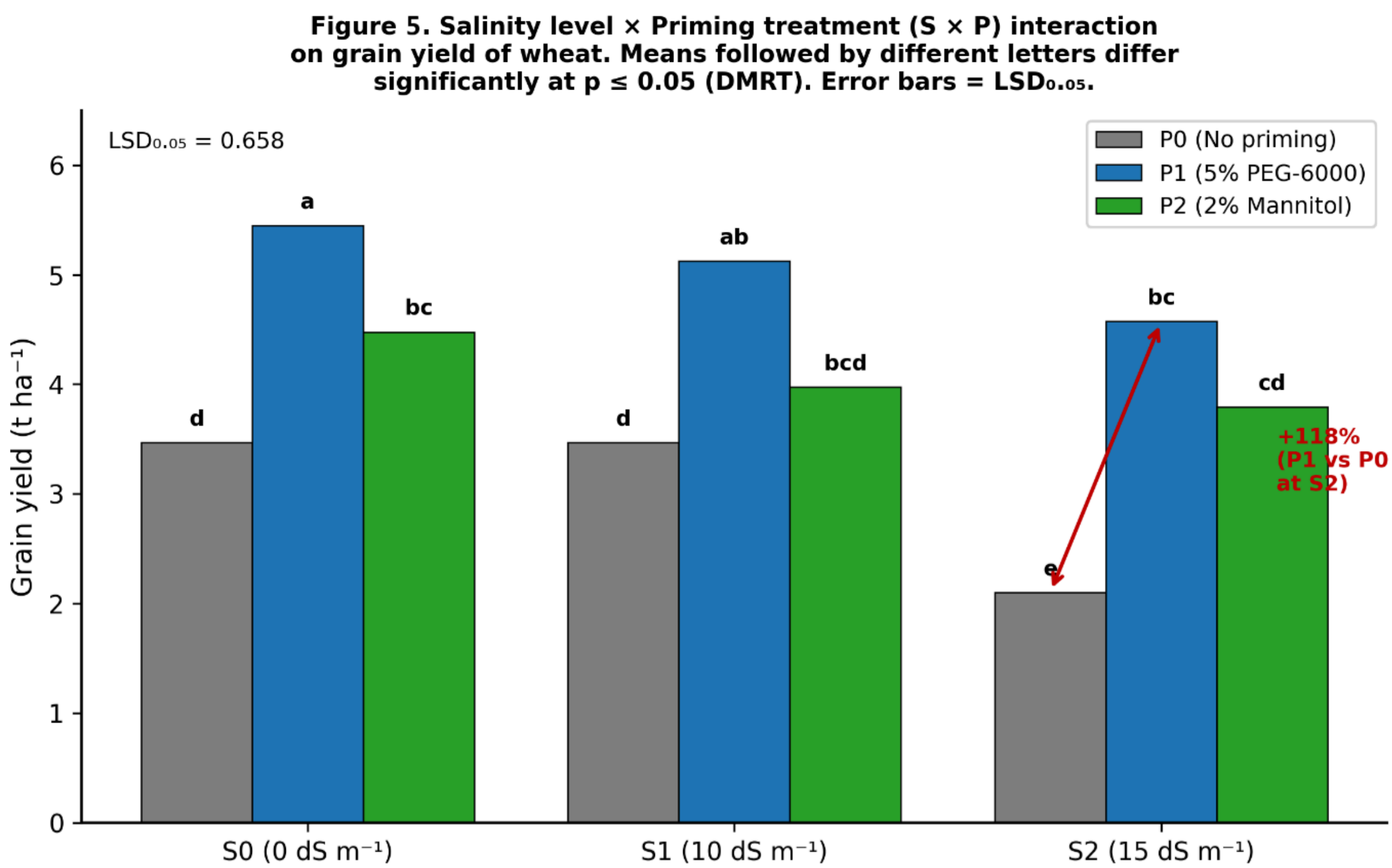

Figure 5

Salinity level × Priming treatment (S×P) interaction on grain yield (t ha^{-1}). The double-headed arrow indicates the 118% improvement of 5% PEG-6000 (P1) over no priming (P0) at 15 dS m^{-1} (S2). Error bars = $LSD_{0.05}$ = 0.658. Different letters above bars denote significant differences (DMRT, $p \leq 0.05$)

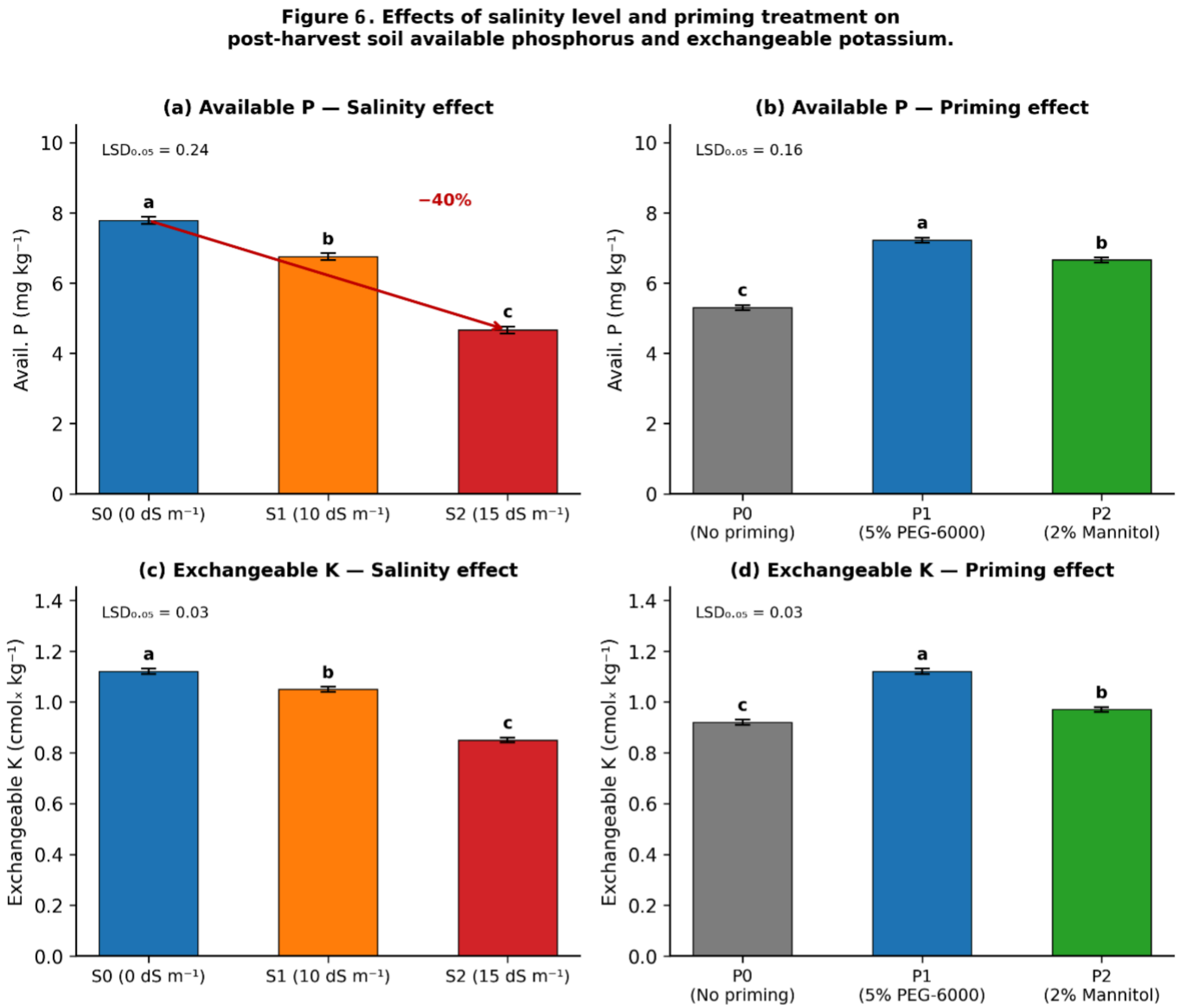

Figure 6

Effects of (a,c) salinity level and (b,d) priming treatment on post-harvest soil available phosphorus (mg kg^{-1}) and exchangeable potassium (cmol$_c$ kg^{-1}). The −40% annotation indicates phosphorus reduction from S0 to S2. Error bars = $LSD_{0.05}$. Different letters denote significant differences (DMRT, $p \leq 0.05$)