

Micronutrient and Growth Regulator Seed Priming -Enhanced Salt Stress Resilience in Rice (*Oryza sativa*)

Mbaraka Abbakari Batare¹, Dastun Gabriel Msuya², Beatrice Victor Mwaipopo³

^{1,2,3}Sokoine University of Agriculture, College of Agriculture, Department of Crop Science and Horticulture, P. O. Box 3005, Chuo-Kikuu, Morogoro, Tanzania.

¹Tanzania Agricultural Research Institute (TARI) – Dakawa, P. O. Box 1892, Morogoro, Tanzania.

Abstract

Soil salinity is a major constraint to rice production in sub-Saharan Africa, limiting yield and productivity. This study evaluated the effectiveness of seed priming in enhancing growth and yield performance of rice (*Oryza sativa*) in salt-affected soils. Seeds of five rice cultivars were primed with gibberellic acid (GA), zinc (Zn), GA+Zn, water, or left unprimed (control) in a factorial experiment arranged in a randomized complete block design with three replications. Data were collected at tillering, booting, and maturity stages, and analyzed using ANOVA. Results showed that GA and GA+Zn priming significantly ($p < 0.05$) improved performance across most traits. The highest mean grain yields were recorded in GA+Zn (3.9 t ha^{-1}), GA (3.8 t ha^{-1}), and Zn (3.5 t ha^{-1}) treatments, compared to 2.5 t ha^{-1} in water-primed and unprimed controls. Among cultivars, SATO1 (GA) achieved the highest yield (5.51 t ha^{-1}), followed by SATO1 (GA+Zn, 4.74 t ha^{-1}) and TXD306 (GA+Zn, 4.06 t ha^{-1}), indicating genotype-specific responses to priming. Priming also increased filled grain number and reduced sterility and salt injury across cultivars. Overall, seed priming particularly with GA and GA+Zn enhanced rice resilience and productivity under saline conditions. Integrating priming into existing rice production systems offers a simple, low-cost strategy to improve yields and promote food security in salt-affected environments.

Keywords: Abiotic stress; Rice yield; Salinity tolerance; Seed priming; Tanzania.

1.0 Introduction

Rice (*Oryza sativa*) serves as a staple food for over half of the world's population, providing essential carbohydrates and nutrients that meet daily dietary needs (Alam et al., 2024; Hijam et al., 2025). Beyond nutrition, rice plays a central role in global food security and economic stability. It is deeply embedded in cultural and social traditions, especially in Asia, where it is often referred to as "the grain of life" (Kumar et al., 2023; Radanova, 2023). The crop is cultivated across diverse environments from irrigated lowlands and rainfed uplands to flood-prone areas, due to its adaptability to varying climatic and soil

conditions (Bhuyan et al., 2024; Bwire et al., 2024). Asia leads global rice production, accounting for approximately 90% of the total output, with China, India, and Indonesia being the largest producers (FAO, 2020; Mokhtar et al., 2024). China alone produces around 210 million tons annually, followed by India at 175 million tons (Ashraf et al., 2024; Anandan et al., 2024), while Indonesia and Bangladesh contribute between 30–35 million tons each (Al Mamun et al., 2024; Susanti et al., 2024), whereas world rice production (milled basis) is forecast to reach 523.9 million tonnes in the 2023/24 period (FAO, 2024).

Global rice cultivation has expanded significantly over the past two decades. Between 2000 and 2019, production increased from 600 million to over 780 million tons, with an average annual growth rate of 1.5% (Connor et al., 2023). This growth is largely attributed to advancements in agricultural practices, including the development of high-yielding varieties and improved irrigation techniques (Jyoti et al., 2024; Mthiyane et al., 2024).

Despite these gains, rice production faces multiple sustainability challenges. Climate change, characterized by rising temperatures and erratic rainfall, threatens yield stability especially during critical growth stages like flowering and grain filling (Jyothsna et al., 2024; Li et al., 2024a). Among the emerging threats, soil salinity has become another serious constraint, particularly in coastal and low-lying areas where rice is commonly grown. Saline soils hinder nutrient uptake and induce physiological stress, leading to poor crop performance (Hussain et al., 2024; Ji et al., 2024).

Various strategies have been employed to address salinity stress. Breeding for salt-tolerant cultivars has shown promise (Khanna et al., 2024; Saminadane et al., 2024), alongside integrated soil and water management practices such as the use of organic amendments, improved irrigation methods, and crop rotation (Irin & Hasanuzzaman, 2024; Zhu et al., 2024). Another emerging strategy is seed priming, a pre-sowing treatment that enhances seed vigor and improves establishment under stress conditions (Houmani et al., 2024; Anwar et al., 2024; Jarrar et al., 2024).

Although seed priming has been evaluated in several crops, its application in rice, particularly under Tanzanian conditions, remains largely unexplored. Salinity has become a growing concern across many of Tanzania's irrigation schemes, manifesting as saline, sodic, or saline-sodic soils. As the country population increases, boosting rice productivity under such stress conditions is imperative. Farmers' traditional efforts appear insufficient, necessitating integrated solutions. However, knowledge gaps persist particularly regarding how seed priming and priming methods influence rice establishment, vigor, and yield under saline environments. Moreover, differential responses of rice varieties to priming under salinity stress have not been documented.

Therefore, this study aims to fill these knowledge gaps by examining the effects of seed priming methods in enhancing rice resilience to salinity, with a focus on varietal differences. The goal is to support adaptation and mitigation strategies for improved rice productivity and food security in Tanzania and the broader region.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in Chanzuru Village, Kilosa District, located in the Morogoro Region of eastern Tanzania. The area is characterized by diverse agro-ecological conditions that provide a favourable environment for rice cultivation. Chanzuru lies approximately between 6°45' and 6°55' S latitude and 37°30' and 37°40' E longitude, at an altitude of about 460 meters above sea level (Mfupe et al., 2024). The average annual rainfall ranges from 800 to 1,200 mm, with most precipitation occurring during the long rainy season. Soils in the area vary but are generally classified as alluvial, offering good fertility for rice production. The region features lowland ecosystems that are vital for rice cultivation, as they are frequently flooded during the rainy season, ensuring adequate soil moisture. The main rice-growing season coincides with the long rains, typically from March to June, while a secondary season occurs during the short rains from October to December. Notably, the area is salt-affected, making it a suitable site for studies addressing salinity-related challenges in rice cultivation.

2.2 Soil sampling and Analysis

A baseline survey was initially conducted in the field to identify salt films and indicators of salinity, confirmed using a portable electrical conductivity (EC) meter and supported by previous studies by Omar et al. (2022, 2024). Soil samples were then collected from various areas characterized by salt-affected soils. A random zigzag sampling technique was employed prior to field preparation, focusing on a depth of 0-30 cm. The collected samples from each site were combined to form a composite sample of 1.5 kg for laboratory analysis in accordance with procedures detailed by Okalebo et al. (2002). Soil analysis was done at the International Institute of Tropical Agriculture (IITA) laboratory in Mikocheni Dar es salaam Tanzania. Key soil parameters analyzed to determine the type and extent of salt affected soil included pH, EC and Exchangeable Sodium Percent (ESP). Additional soil fertility standard indicators were also analysed, including organic carbon (OC), nitrogen (N), texture, along with phosphorus (P), zinc (Zn), iron (Fe), calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na). The analysis typically indicated the soil used for this experiment has high pH of 8.7, EC of 7.02 dS/m, and ESP of 48%. According to Zamora Re et al. (2022), the outlined soil can be classified as saline-sodic. A summary of all soil parameter results is presented in Table 1.

Table 1: Physicochemical properties of soils at the Chanzuru study site

Soil Parameter	Value	Soil Parameter	Value
pH	8.7	Zn (mg kg ⁻¹)	1.13
EC (mhos cm ⁻¹)	7.02	Fe (mg kg ⁻¹)	86.7
CEC (Cmol ⁺ /kg)	6.8	Ca (cmol ⁺ kg ⁻¹)	7.98
OC (%)	0.56	Mg (cmol ⁺ kg ⁻¹)	10.44
N (%)	0.08	K (cmol ⁺ kg ⁻¹)	0.14
ESP	48	Na (cmol ⁺ kg ⁻¹)	3.26
Textural class	Sandy Clay	Description	Saline-sodic
P (mg kg ⁻¹)	8.16		

2.3 Experimental Design and Treatments

The study employed a factorial experiment arranged in a Randomized Completely Block Design (RCBD) to evaluate the effects of seed priming on different rice cultivars. Two factors were considered: genotype (rice varieties) and priming. The variety factor consisted of five rice cultivars: KALAMATA (a local variety), SATO1 (improved for salt tolerance), TARI RIC2, TARI RIC3, and TXD306 (SARO 5) which are most preferred by farmers. The priming factor also comprised of five levels: gibberellic acid (GA), zinc (Zn), a combination of GA and Zn, water, and a non-primed control. This resulted in a total of 25 distinct treatment combinations (5 varieties $\times$ 5 priming methods). The experiment was replicated three times (blocks), with all treatment combinations randomly assigned within each replication.

2.4 Seed Priming

Gibberellic acid (GA) was prepared at a concentration of 100 ppm by dissolving 0.1g in 1 L of distilled water, while zinc (Zn) was prepared by dissolving 50 g of Zn in 1 L of distilled water. Hormonal priming; rice seeds were soaked in 100 ppm GA solution for 24 hours, followed by air-drying for 6 hours before sowing. Micronutrient (Zn) priming; rice seeds were soaked in 0.5% zinc sulfate (ZnSO_4) solution for 24 hours, followed by air-drying for 6 hours before sowing to reduce moisture content up to 12% (Kumar, et al 2020). Hydro priming; rice seeds were soaked in water for 24 hours followed by air drying for 6 hours before sowing and mixture of GA +Zn, seed was soaked in solution of (100 ppm GA + 0.5% zinc sulfate (ZnSO_4)) followed by air-drying for 6 hours before sowing to reduce moisture content up to 12%. After priming, seeds were directly sown by drilling into furrows 2–3 cm deep, with a row spacing of 25 cm. Each treatment was established in a plot measuring 8 m². Following the approaches of Awio et al. (2021) and Senthilkumar et al. (2021), synthetic fertilizers were applied to correct nitrogen (N) and phosphorus (P) deficiencies. Di-ammonium phosphate (DAP), containing 18% N and 46% P_2O_5 , was uniformly applied at planting, supplying 40 kg P ha⁻¹ and 36 kg N ha⁻¹. To achieve a total of 100 kg N ha⁻¹, an additional 64 kg N ha⁻¹ was provided using urea (46% N), applied in two equal splits once at the tillering stage and again at the booting stage each contributing 32 kg N ha⁻¹.

2.5 Data Collection

Data were collected at three critical growth stages of rice: initial tillering, booting, and maturity. At the initial tillering stage, various growth parameters were measured to assess the early response to seed priming under salt-affected conditions. These included plant height in centimetres, root dry weight and root fresh weight in grams, root length in centimetres, number of roots per plant, shoot dry weight and shoot fresh weight in grams, and the number of tillers per square meter. The same set of measurements was repeated at the booting stage to monitor changes in plant development except for shoot and root dry weight. At maturity, data collection focused on growth, yield, and yield components, including plant height, panicle length in centimetres, panicle weight in grams, number of panicles per square meter, and a salt injury score. Additional measurements taken at this stage were days to maturity, biomass in grams per square meter, number of filled and unfilled grains per panicle, 1000-grain weight in grams, and grain yield per plot, which was later converted to grain yield per hectare in tons per hectare.

2.6 Statistical Analysis

A two-way analysis of variance (ANOVA) was conducted to assess the effects of seed genotype and priming treatments on rice growth and yield. The analysis examined the main effects of both factors as well as their interaction. Where significant differences were detected, Tukey's post hoc test was applied to identify specific differences among treatment means.

3.0 Results

3.1 Analysis of variance

The analysis of variance (ANOVA) results are presented in Tables 2–4, with growth parameters at initial tillering (Table 2) and booting (Table 3), and growth, yield, and yield components at maturity (Table 4). The results revealed differential effects of seed priming and genotype across rice growth stages. At the initial tillering stage, the genotype factor significantly influenced plant height ($p < 0.001$) and shoot fresh weight ($p < 0.01$), while other traits were not significant. For the priming factor, six parameters; root dry weight, root fresh weight, number of roots per plant, shoot dry weight, shoot fresh weight, and number of tillers per square meter were highly significant at the 0.1% level, whereas root length was significant at the 1% level and plant height was not significant at the 5% level. No traits showed significant interaction effects between priming and genotype even at the 5% threshold.

At the booting stage (Table 3), plant height, number of tillers, and shoot fresh weight were statistically significant for the genotype factor ($p < 0.001$), while the remaining traits were not significant. For the priming factor, number of roots per plant was significant at $p < 0.001$ and shoot fresh weight at $p < 0.01$, whereas the other traits were non-significant. None of the interaction effects were significant for any parameter.

At the maturity stage (Table 4), several parameters showed significant variation among genotypes: plant height, number of panicles, panicle length, thousand-grain weight, days to maturity and grain yield ($p < 0.001$), and panicle weight ($p < 0.01$). Number of filled grains, unfilled grains, salt injury score and biomass were not significant. For priming methods, significant variation was observed in plant height, number of panicles, panicle weight, thousand-grain weight, filled grains per panicle, salt injury score, days to maturity, grain yield, and biomass ($p < 0.001$), as well as panicle length ($p < 0.01$) and unfilled grains per panicle ($p < 0.05$). Only grain yield was significant for the interaction between priming and genotype.

Table 2. Mean squares from the analysis of variance (ANOVA) showing the main effects of genotype, priming methods, and their interaction at the initial tillering stage.

Source of variation	D.f.	Plant height	Number of tillers	Root length	Number roots per plant	Shoot per fresh weight	Root fresh weight	Shoot dry weight	Root dry weight
Replication	2	162.9	1.4	15.3	1119.5	107.6	25.4	4.3	0.6
Genotype	4	729.0***	4.8	11.5	275.8	151.4**	2.2	6.1	0.4
Priming	4	66.0	48.9***	37.2**	2064.4***	623.8***	336.6***	33.3***	13.3***
Genotype × Priming	16	72.5	1.2	12.9	380.9	44.5	34.1	1.4	0.9
Residual	48	70	1.4	7.1	337	38.5	29.1	2.6	1.0

Key: * = significant at 5% ($p < 0.05$); ** = significant at 1% ($p < 0.01$); *** = significant at 0.1% ($p < 0.001$)

Table 3: Mean squares from the analysis of variance (ANOVA) showing the main effects of genotype, priming methods, and their interaction at the booting stage.

Source of variation	D.f.	Plant height	Number of tillers	Root length	Number roots per plant	Shoot fresh weight	Shoot fresh weight	Days to 50% flowering
Replication	2	321.4	5.7	6.0	195.1	37.8	56.5	7.9
Genotype	4	3222.2***	36.4***	18.7	910.5	26.8	2031.5***	439.3
Priming	4	290.0	8.7	11.8	2829.2***	60.3	1660.5**	2.0
Genotype × Priming	16	143.1	3.0	9.2	257.6	29.9	368.2	161.3
Residual	48	229.7	6.5	9.1	365.6	31.4	322.5	5.1

Key: * = significant at 5% ($p < 0.05$); ** = significant at 1% ($p < 0.01$); *** = significant at 0.1% ($p < 0.001$)

Table 4: Mean squares from the analysis of variance (ANOVA) showing the main effects of genotype, priming methods, and their interaction at the maturity stage.

Source of variation	D.f.	Plant height	Number of panicles	Panic length	Panic weight	Thousand-grain weight	Filled grains per panicle	Unfilled grains per panicle	Salt injury score	Days to maturity	Grain yield	Biomass
Replication	2	39.8	25,990	11.9	2.9	2.2	198	587.6	14.6	7.9	3.1	12,872
Genotype	4	3,037.0*	36,051*	43.1*	6.9**	71.9***	5,229	1,264.	1.2	439.3*	1.7*	40,495

Source of variation	D. f.	Plant height	Number of panicles	Panic length	Panic weight	Thousand-grain weight	Filled grains per panicle	Unfilled grains per panicle	Salt injury score	Days to maturity	Grain yield	Biomass
e		**	**	**				5		**	**	
Priming	4	562.4** *	47,251* **	28.8* *	16.3* **	55.6***	22,146* **	3,032. 7	10.4* **	161.3* **	7.2* **	342,029* **
Genotype	× 16	64.5	3,625	7.6	1.7	2.4	2,482	748.9	2.3	5.1	0.8*	29,287
Priming												
Residual	48	77.9	4,743	7.0	1.7	2.1	2,381	711.4	1.9	4.2	0.3	–

Key: * = significant at 5% ($p < 0.05$); ** = significant at 1% ($p < 0.01$); *** = significant at 0.1% ($p < 0.001$).

3.2 Effects of seed priming on growth, yield, and yield components in rice

The effects of seed priming on agronomic parameters at initial tillering, booting, and maturity are summarized in Tables 5, 6, and 7, respectively, with results presented only for traits that exhibited significant variation in the analysis of variance.

At the tillering stage (Table 5), root fresh weight was highest in GA-primed seeds (16 g), followed by GA+Zn (14.1 g) and Zn (10.0 g), while water-primed and unprimed seeds produced the lowest values (5.7 and 5.6 g), which did not differ significantly. For root dry weight, GA (3.4 g), GA+Zn (2.8 g), and Zn (2.4 g) were statistically similar and significantly higher than water (1.4 g) and unprimed (1.2 g). A similar trend was observed for shoot fresh weight, where GA (23.3 g), GA+Zn (17.1 g), and Zn (22.1 g) were significantly superior to water (10.1 g) and unprimed (9.6 g). Root length was greatest in GA (13.1 cm) and GA+Zn (12.8 cm), with Zn (10.7 cm) intermediate and comparable to both the higher and lower groups (water, 9.6 cm; unprimed, 10.2 cm). Shoot dry weight also followed the same pattern, with GA (5.7 g), GA+Zn (5.2 g), and Zn (4.2 g) outperforming water (2.6 g) and unprimed (2.5 g). The number of roots per plant was highest in GA (81.1), statistically similar to GA+Zn (78.6) and Zn (73.6), while water (57.6) and unprimed (56.3) produced the fewest roots. The number of tillers was highest in GA (7.2), statistically similar to Zn (6.6), while GA+Zn (5.9) did not differ significantly from Zn. The lowest and statistically similar number of tillers was recorded in water (3.6) and unprimed (3.3).

Table 5: Effect of seed priming treatments on early growth parameters of rice at the initial tillering stage

Priming treatments	Root dry weight (g)	Root fresh weight (g)	Root length (cm)	Number of roots plant	Shoot dry weight (g)	Shoot fresh weight (g)	Number of tillers
--------------------	---------------------	-----------------------	------------------	-----------------------	----------------------	------------------------	-------------------

Priming treatments	Root dry weight (g)	Root fresh weight (g)	Root length (cm)	Number of roots per plant	Shoot dry weight (g)	Shoot fresh weight (g)	Number of tillers
GA (Gibberellic acid)	3.4a	16a	13.1a	81.1a	5.7a	23.3a	7.2a
Zn (Zinc)	2.4a	10.0bc	10.7ab	73.6ab	4.2ab	17.1a	6.6ab
GA + Zn	2.8a	14.1ab	12.8a	78.6a	5.2a	22.1a	5.9b
Water	1.4b	5.7c	9.6b	57.6b	2.6bc	10.1b	3.6c
Unprimed (Control)	1.2b	5.6c	10.2b	56.3b	2.5c	9.6b	3.3c
Grand mean	2.25	10.28	11.26	69.4	4.04	16.41	5.32
LSD (5%)	0.745	3.949	1.773	12.78	1.236	4.66	0.783
SE (±)	0.27	1.43	0.64	4.61	0.45	1.68	0.28
CV (%)	12.0	13.9	5.7	6.6	11.1	10.2	5.3
p-value	<0.001	<0.001	<0.01	<0.001	<0.001	<0.001	<0.001

Key: *Means within a column followed by different letter(s) differ significantly at the 5% error rate ($p < 0.05$); means sharing the same letter are not statistically different.

At the booting stage (Table 6), days to 50% flowering were shortest in Zn- and GA+Zn-primed seeds (77 days), significantly earlier than GA (79.7 days), water (84.1 days), and unprimed (83.3 days). The number of roots was significantly higher in GA (104.1), Zn (105.9), and GA+Zn (109.2) compared to water (82.2) and unprimed (81.0). Shoot fresh weight was also enhanced by GA (55.1 g), GA+Zn (54.1 g), and Zn (40.6 g), which were significantly greater than water (36.6 g) and unprimed (31.6 g).

Table 6: Effect of seed priming treatments on rice growth parameters at booting and flowering stage

Priming treatments	Days to flowering	50% Number of roots per plant	Shoot fresh weight (g)
GA (Gibberellic acid)	79.7b	104.1a	55.1a
Zn (Zinc)	77.4c	105.9a	40.6abc
GA + Zn	77.0c	109.2a	54.1ab
Water	84.1a	82.2b	36.6bc
Unprimed (Control)	83.3a	81.0b	31.6c
Grand mean	80.31	96.5	43.6

Priming treatments	Days to flowering	50% Number of roots per plant	Shoot fresh weight (g)
LSD (5%)	1.578	14.91	12.38
SE ($\pm$)	0.57	5.38	4.47
CV (%)	0.7	5.6	10.2
p-value	<0.001	<0.001	<0.001

Key: *Means within a column followed by different letter(s) differ significantly at the 5% error rate ($p < 0.05$); means sharing the same letter are not statistically different.

At maturity (Table 7), GA (32.5 g), Zn (32.2 g), and GA+Zn (32.3 g) produced the highest thousand grain weights, significantly greater than water (29.0 g) and unprimed (28.7 g). A similar trend was observed for biomass, grain yield, and panicle weight. Filled grains per panicle were significantly higher in GA (230.4), Zn (248.5), and GA+Zn (259.6) compared to water (174.1), while GA was statistically similar to unprimed (184.2). GA+Zn produced the longest panicles (21.2 cm), statistically comparable to GA (20.6 cm) and Zn (19.4 cm), but significantly longer than water (17.0 cm) and unprimed (17.4 cm). The number of panicles per unit area was highest in GA (457.1), GA+Zn (447.9), and Zn (436.8), all superior to water (385.5), with Zn statistically similar to unprimed (418.3). A comparable trend was observed for plant height, except that Zn was similar to water but greater than unprimed. Salt injury scores were lowest in GA (3.3), Zn (3.5), and GA+Zn (3.8), which were statistically similar and generally lower than water (4.6) and unprimed (4.8). Seed priming treatments significantly influenced the days to maturity of rice ($p < 0.001$). Seeds primed with GA, Zn, and GA+Zn matured earlier (112–115 days) compared to water-primed and unprimed seeds, which reached maturity at 118–119 days. Among the treatments, Zn and GA+Zn recorded the shortest maturity periods (112–112.4 days), highlighting their role in accelerating crop development under the tested conditions.

Table 7: Effects of priming treatments on rice at maturity

Priming treatments	Thousand grain weight (g)	Biomass (g/m ²)	Filled grain per panicle	Grain yield (t/ha)	Panicle length (cm)	Panicle weight (g)	Number of panicles (m ²)	Plant height (cm)	Salt injury score	Days to maturity
GA	32.5a	1155a	230.4ab	3.8a	20.6ab	8.0a	457.1a	84.7a	3.3c	114.7b
Zn	32.2a	1129a	248.5a	3.5a	19.4ab	8.1a	436.8ab	82.8ab	3.5bc	112.4c
GA+Zn	32.3a	1075a	259.6a	3.9a	21.2a	8.7a	447.9a	84.5a	3.8abc	112c
Water	29b	827b	174.1c	2.5b	18.1b	6.7b	331.9c	74.4bc	5.1a	119.1a
Unprimed	28.7b	875b	183.7bc	2.5b	18.2b	6.2b	363.5bc	71.7c	4.9ab	118.3a
Grand mean	30.93	1012	219.3	3.255	19.5	7.57	407.5	79.6	4.12	115.31
L.S.D.	1.09	114.8	35.43	0.374	2.009	0.928	52.61	6.43	1.019	1.578
p value	<0.001	<0.001	<0.001	<0.001	0.009	<0.001	<0.001	<0.001	0.001	<0.001

Key: *Means within a column followed by different letter(s) differ significantly at the 5% error rate ($p < 0.05$); means sharing the same letter are not statistically different.

3.3 Varietal and priming interaction effects on yield

Grain yield was the only parameter that showed a significant interaction between priming and genotype, indicating that yield performance under salt-affected conditions is both genotype- and priming-dependent. The combination of SATO1–GA produced the highest yield (5.51 t/ha), although it was not significantly different from SATO 1–GA+Zn, TXD306–GA+Zn, SATO 1–Zn, TXD306–GA, and KALAMATA–GA+Zn, all of which recorded mean yields slightly below 5.0 t/ha (Table 8). Notably, although grouped with some statistically similar treatments, the mean yield of SATO 1–GA was significantly higher than most other treatment combinations. The lowest yield was observed in TXD306–Unprimed (1.97 t/ha), which was statistically comparable to 18 other treatment combinations (sharing letter “f” in the mean comparison). Overall, treatments involving unprimed or water-primed seeds consistently produced the lowest yields compared to primed treatments across genotypes.

Table 8: Interaction effects of priming and genotype on yield

Genotype x Priming	Mean Yield	
SATO 1-GA	5.51	a
SATO 1-GA+Zn	4.74	ab
TXD306-GA+Zn	4.06	a-c
SATO 1-Zn	3.90	a-d
TXD306-GA	3.89	a-d
KALAMATA-GA+Zn	3.81	a-e
TXD306-Zn	3.63	b-f
TARI RIC2-GA+Zn	3.61	b-f
KALAMATA-Zn	3.57	b-f
TARI RIC3-GA+Zn	3.38	b-f
TARI RIC3-Zn	3.36	b-f
KALAMATA-GA	3.29	b-f
TARIC RIC3-GA	3.27	b-f
TARI RIC2-GA	3.17	b-f
TARI RIC2-Zn	2.94	c-f
SATO 1-Unprimed	2.90	c-f
TARI RIC2-Unprimed	2.88	c-f
TARI RIC2-Water	2.83	c-f
TARI RIC3-Water	2.62	c-f
TXD306-Water	2.57	c-f
KALAMATA-Water	2.54	c-f
TARI RIC3-Unprimed	2.48	c-f
KALAMATA-Unprimed	2.26	d-f

SATO 1-Water	2.11	ef
TXD306-Unprimed	1.96	f

*Means in each column bearing different letter(s) differ significantly at 5% error rate.

4. Discussion

This study demonstrates that seed priming enhances rice resilience to salt stress by improving physiological growth and yield traits. The use of gibberellic acid (GA), zinc (Zn), and their combination improved plant performance across growth stages, consistent with earlier reports that priming promotes crop establishment, vigour, and productivity under stress (Mathpal et al., 2023; Nazir et al., 2024).

Most agronomic traits showed no significant genotype $\times$ priming interaction, except for grain yield, indicating that priming effects were generally consistent across cultivars. Root traits responded strongly to priming, particularly with GA and Zn, contributing to improved water and nutrient uptake under saline conditions. These findings align with Ellouzi et al. (2024) and Zhang et al. (2024), who linked robust root systems to stress adaptation. The limited response of some genotypes may reflect inherent differences in root plasticity (Ganie et al., 2024; Libron et al., 2024), suggesting potential for breeding programs to incorporate such adaptive traits.

Above-ground growth was also enhanced by priming, notably under GA and Zn treatments, while unprimed and water-primed plants performed poorly. Plant height varied mainly at maturity, but yield components; key determinants of productivity benefited significantly from GA, Zn, and GA+Zn. Primed plants also showed reduced salt injury, indicating enhanced physiological tolerance. Similar effects have been reported by Li et al. (2023) and Zhang et al. (2022), who emphasized the synergistic role of seed priming and genotypic tolerance in maintaining yield and quality under salinity. These findings support the potential of seed priming as a complementary approach to genetic improvement in stress environments.

Grain yield varied among cultivars and priming treatments, confirming a significant genotype $\times$ priming interaction. The highest yield was recorded in SATO 1 primed with GA, followed by other GA-, Zn-, and GA+Zn-treated genotypes. These results, consistent with Samota et al. (2024) and Dueñas et al. (2024), highlight the need to align priming strategies with genotype characteristics to maximize yield benefits. Seed priming also influenced flowering and maturity, where GA and Zn treatments accelerated crop development, an advantage for escaping late-season stress. This agrees with Dharni et al. (2024), who reported priming-induced advancement in phenology. Under increasing climate variability, such shifts can improve synchronization with favourable growing conditions (De Vos et al., 2023; Jamal et al., 2023).

Overall, hormonal and micronutrient priming proved effective in enhancing growth, yield, and stress resilience. The consistent superiority of GA- and Zn-based priming confirms its value as a low-cost, scalable technology for improving rice performance under saline and climate-stressed environments (Hu et al., 2024; Wen et al., 2024). Future research should explore the physiological and molecular mechanisms underlying genotype-specific responses and evaluate multi-season or multi-location effects to refine seed priming strategies for resilient rice production systems (Suvi et al., 2021).

5. Conclusion and Recommendations

This study confirms that seed priming with micronutrient zinc (Zn) and the growth regulator gibberellic acid (GA) significantly enhances rice performance under salt stress by improving growth and grain yield. Among the treatments, GA, Zn and GA+Zn priming achieved the highest yields ($>3.0 \text{ t ha}^{-1}$), outperforming water-primed and unprimed seeds. The cultivar SATO 1 treated with GA produced the highest yield (5.5 t ha^{-1}), followed by SATO 1 and TXD 306 treated with GA+Zn ($>4.0 \text{ t ha}^{-1}$). In contrast, water-primed and unprimed treatments yielded below 3.0 t ha^{-1} , with unprimed TXD 306 recording the lowest (1.96 t ha^{-1}). These results suggest that GA and GA+Zn seed priming are effective, low-cost strategies for improving rice productivity in saline environments. It is therefore recommended that extension programs promote the adoption of seed priming practices. Further studies should focus on genotype–priming interactions and long-term field validation to strengthen climate- and stress-resilient rice production systems.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

MAB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, writing original draft, Writing review & editing. DGM: Supervision, Validation, Visualization, Writing review & editing. BVM: Supervision, Validation, Visualization, Writing review & editing.

Funding

The authors declare that financial support was received for the research, authorship, and publication of this article. Material and financial support were provided by Tanzania agriculture research institute (TARI) and International Rice Research Institute (IRRI). The views and opinions expressed in this publication are solely those of the authors and do not necessarily reflect the views of IRRI or any affiliated organizations. The authors extend their gratitude to all IRRI partners and field staff for their support throughout this research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

1. Al Mamun, M. A., Nihad, S. A. I., Sarker, M. R., Sarkar, M. A. R., Hossain, M. I., & Kabir, M. S. (2024). Spatiotemporal mapping of rice acreage and productivity growth in Bangladesh. *Plos one*, 19(3), e0300648. <https://doi.org/10.1371/journal.pone.0300648>
2. Alam, M., Lou, G., Abbas, W., Osti, R., Ahmad, A., Bista, S. & He, Y. (2024). Improving rice grain quality through ecotype breeding for enhancing food and nutritional security in Asia–pacific region. *Rice*, 17(1), 47. <https://doi.org/10.1186/s12284-024-00725-9>
3. Anandan, A., Panda, S., Mahender, A., & Murugaiyan, V. (2024). Breeding rice variety with suitable plant ideotype for next-generation Indian agriculture in the changing climatic conditions. In *climate change impacts on soil-plant-atmosphere continuum*. Singapore: Springer Nature Singapore (pp. 507-528). https://doi.org/10.1007/978-981-99-7935-6_19
4. Anwar, M. P., Akhter, M., Aktar, S., Kheya, S. A., Islam, A. K. M., Yeasmin, S., ... & Or Rashid, M. H. (2024). Relationship between seed priming mediated seedling vigor and yield performance of spring wheat. *Phyton* (0031-9457), 93(6). <https://doi.org/10.32604/phyton.2024.049073>
5. Ashraf, H., Ghouri, F., Baloch, F. S., Nadeem, M. A., Fu, X., & Shahid, M. Q. (2024). Hybrid rice production: A worldwide review of floral traits and breeding technology, with special emphasis on China. *Plants*, 13(5), 578. <https://doi.org/10.3390/plants13050578>
6. Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Kempen, B., Struik, P. C., & Stomph, T. J. (2021). Micro-nutrients in East African lowlands: Are they needed to intensify rice production? *Field Crops Research*, 270, 108219. <https://doi.org/10.1016/j.fcr.2021.108219>
7. Bhuyan, G. V., Deka, N., & Bhagabati, A. K. (2024). Rice farming in Assam (India): Ecology, tradition, and transformation. In *Sacred Landscapes, Indigenous Knowledge, and Ethno-culture in Natural Resource Management: Understanding Multiple Perspectives of Nature Conservation* (pp. 189-207). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-4206-6_9
8. Bwire, D., Saito, H., Sidle, R. C., & Nishiwaki, J. (2024). Water management and hydrological characteristics of paddy-rice fields under alternate wetting and drying irrigation practice as climate smart practice: A Review. *Agronomy*, 14(7), 1421. <https://doi.org/10.3390/agronomy14071421>
9. Connor, M., Malabayabas, A. J. B., de Guia, A. H., Wehmeyer, H., Pame, A. R. P., Htwe, N. M., ... & Tuan, L. A. (2023). Environmental, social, and economic challenges in lowland rice production. In *Closing rice yield gaps in Asia: innovations, scaling, and policies for environmentally sustainable lowland rice production* (pp. 27-92). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-37947-5_2
10. De Vos, K., Janssens, C., Jacobs, L., Campforts, B., Boere, E., Kozicka, M., ... & Govers, G. (2023). Rice availability and stability in Africa under future socio-economic development and climatic change. *Nature food*, 4(6), 518-527. <https://doi.org/10.1038/s43016-023-00770-5>

11. Dharni, J. S., Shi, Y., Zhang, C., Petersen, C., Walia, H., & Staswick, P. (2024). Growth and transcriptional response of wheat and rice to the tertiary amine BMVE. *Frontiers in Plant Science*, 14, 1273620. <https://doi.org/10.3389/fpls.2023.1273620>
12. Dueñas Jr, C., Pagano, A., Calvio, C., Srikanthan, D. S., Slamet-Loedin, I., Balestrazzi, A., & Macovei, A. (2024). Genotype-specific germination behavior induced by sustainable priming techniques in response to water deprivation stress in rice. *Frontiers in Plant Science*, 15, 1344383. <https://doi.org/10.3389/fpls.2024.1344383>
13. Ellouzi, H., Ben Slimene Debez, I., Amraoui, S., Rabhi, M., Hanana, M., Alyami, N. M., ... & Zorrig, W. (2024). Effect of seed priming with auxin on ROS detoxification and carbohydrate metabolism and their relationship with germination and early seedling establishment in salt stressed maize. *BMC Plant Biology*, 24(1), 704. <https://doi.org/10.1186/s12870-024-05413-w>
14. FAO. (2020). FAO Rice Market Monitor. Food and Agriculture Organization of the United Nations. <http://www.fao.org/economic/est/publications/rice-publications/rice-market-monitor-rmm/en/>
15. Food and Agriculture Organization of the United Nations (FAO). (2024). FAOSTAT statistical database. Retrieved September 23, 2025, from <https://www.fao.org/f>
16. Ganie, S. A., McMulkin, N., & Devoto, A. (2024). The role of priming and memory in rice environmental stress adaptation: Current knowledge and perspectives. *Plant, Cell & Environment*, 47(5), 1895-1915. <https://doi.org/10.1111/pce.14855>
17. Hijam, L., Mandal, R., Chakraborty, M., & Maying, B. (2025). Utilization of rice genetic resources for nutritional and medicinal benefits. In *Bioprospecting of Ethnomedicinal Plant Resources* (pp. 351-374). Apple Academic Press. Taylor and Francis Group, UK.
18. Houmani, H., Ben Slimene Debez, I., Turkan, I., Mahmoudi, H., Abdelly, C., Koyro, H. W., & Debez, A. (2024). Revisiting the potential of seed nutri-priming to improve stress resilience and nutritive value of cereals in the context of current global challenges. *Agronomy*, 14(7), 1415. <https://doi.org/10.3390/agronomy14071415>
19. Hu, J., Guan, X., Liang, X., Wang, B., Chen, X., He, X., ... & Chen, J. (2024). Optimizing the nitrogen fertilizer management to maximize the benefit of straw returning on early rice yield by modulating soil n availability. *Agriculture*, 14(7), 1168. <https://doi.org/10.3390/agriculture14071168>
20. Hussain, S., Zhang, R., Chen, Y., Li, J., Hussain, Q., Altaf, A., ... & Dai, Q. (2024). An overview on salt-induced physiological changes, molecular mechanism of salinity tolerance and application strategies for its management in rice. *Cereal Research Communications*, 1-13. <https://doi.org/10.1007/s42976-023-00487-y>
21. Irin, I. J., & Hasanuzzaman, M. (2024). Organic amendments: enhancing plant tolerance to salinity and metal stress for improved agricultural productivity. *Stresses*, 4(1), 185-209. <https://doi.org/10.3390/stresses4010011>
22. Jamal, M. R., Kristiansen, P., Kabir, M. J., & Lobry de Bruyn, L. (2023). Challenges and adaptations for resilient rice production under changing environments in Bangladesh. *Land*, 12(6), 1217. <https://doi.org/10.3390/land12061217>
23. Jarrar, H., El-Keblawy, A., Albawab, M., Ghenai, C., & Sheteiwy, M. (2024). Seed priming as a promising technique for sustainable restoration of dryland. *Restoration Ecology*, e14182. <https://doi.org/10.1111/rec.14182>
24. Ji, J., Zhang, J., Wang, X., Song, W., Ma, B., Wang, R., Li, T., Wang, G., Guan, C., & Gao, X. (2024). The alleviation of salt stress on rice through increasing photosynthetic capacity, maintaining

- redox homeostasis and regulating soil enzyme activities by *Enterobacter* sp. JIV1 assisted with putrescine. *Microbiological Research*, 280, 127590. <https://doi.org/10.1016/j.micres.2023.127590>
25. Jyothsna, K., Aakash, A., Reddy, P. M., & Setty, J. (2024). Impact of temperature variations on rice production. *International Journal of Environment and Climate Change*, 14(5), 1-9. <https://doi.org/10.9734/ijecc/2024/v14i54166>
26. Jyoti, S. D., Singh, G., Pradhan, A. K., Tarpley, L., Septiningsih, E. M., & Talukder, S. K. (2024). Rice breeding for low input agriculture. *Frontiers in Plant Science*, 15, 1408356. <https://doi.org/10.3389/fpls.2024.1408356>
27. Khanna, A., Anumalla, M., Ramos, J., Cruz, M. T. S., Catolos, M., Sajise, A. G., ... & Hussain, W. (2024). Genetic gains in IRRI's rice salinity breeding and elite panel development as a future breeding resource. *Theoretical and Applied Genetics*, 137(2), 37. <https://doi.org/10.1007/s00122-024-04545-9>
28. Kumar, A., Hanjagi, P. S., Saha, S., Mohapatra, S. D., Dash, S. K., Mukherjee, A. K., ... & Molla, K. A. (2023). Extended summaries. Association of rice research workers, ICAR - National Rice Research Institute Cuttack, Odisha.
29. Li, C., Chen, B., Bu, F., Li, L., & Yu, Q. (2024b). OsMYB305 on qATS1 positively regulates alkalinity tolerance at the seedling stage in japonica rice. *Plant Growth Regulation*, 1-13. <https://doi.org/10.1007/s10725-024-01144-y>
30. Li, N., Zhao, Y., Han, J., Yang, Q., Liang, J., Liu, X., ... & Huang, Z. (2024a). Impacts of future climate change on rice yield based on crop model simulation—A meta-analysis. *Science of The Total Environment*, 949, 175038. <https://doi.org/10.1016/j.scitotenv.2024.175038>
31. Li, Z., Zhou, T., Zhu, K., Wang, W., Zhang, W., Zhang, H., Liu, L., Zhang, Z., Wang, Z., Wang, B., Xu, D., Gu, J., & Yang, J. (2023). Effects of salt stress on grain yield and quality parameters in rice cultivars with differing salt tolerance. *Plants*, 12(18), 3243. <https://doi.org/10.3390/plants12183243>
32. Libron, J. A. M. A., Putri, H. H., Bore, E. K., Chepkoech, R., Akagi, I., Odama, E., ... & Sakagami, J. I. (2024). Halopriming in the submergence-tolerant rice variety improved the resilience to salinity and combined salinity-submergence at the seedling stage. *Plant Physiology and Biochemistry*, 208, 108494. <https://doi.org/10.1016/j.plaphy.2024.108494>
33. Mathpal, B., Srivastava, P. C., Pachauri, S. P., Shukla, A. K., & Shankhdhar, S. C. (2023). Role of gibberellic acid and cytokinin in improving grain Zn accumulation and yields of rice (*Oryza sativa* L.). *Journal of Soil Science and Plant Nutrition*, 23(4), 6006-6016. <https://doi.org/10.1007/s42729-023-01459-1>
34. Mfupe, B. P., Msolla, S. N., Chilagane, L. A., & Kashenge-Killenga, S. (2024). The farmer's perception on the yield performance of the different rice genotypes under field conditions in Tanzania. *East African Journal of Science, Technology and Innovation*, 5(3), 1-17.
35. Mokhtar, A., He, H., Nabil, M., Kouadri, S., Salem, A., & Elbeltagi, A. (2024). Securing China's rice harvest: unveiling dominant factors in production using multi-source data and hybrid machine learning models. *Scientific Reports*, 14(1), 14699. <https://doi.org/10.1038/s41598-024-64269-0>
36. Mthiyane, P., Aycan, M., & Mitsui, T. (2024). Strategic advancements in rice cultivation: combating heat stress through genetic innovation and sustainable practices A Review. *Stresses*, 4(3), 452-480. <https://doi.org/10.3390/stresses4030030>
37. Nazir, F., Khatoon, S., Mahajan, M., Kumari, S., AlAjmi, M. F., Rehman, M. T., & Khan, M. I. R. (2024). Enhanced arsenic stress tolerance in landrace and improved rice (*Oryza sativa*) cultivars

- through modulation of gibberellic acid (GA₃) synthesis and antioxidant metabolism via phosphorus and silicon supplementation. *Plant Stress*, 100511. <https://doi.org/10.1016/j.stress.2024.100511>
38. Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis: a working manual second edition*. Sacred Africa, Nairobi, 21, 25-26.
39. Omar, M. M., Shitindi, M. J., Massawe, B. J., Fue, K. G., Pedersen, O., & Meliyo, J. L. (2022). Exploring farmers' perception, knowledge, and management techniques of salt-affected soils to enhance rice production on small land holdings in Tanzania. *Cogent Food & Agriculture*, 8(1), 2140470. <https://doi.org/10.1080/23311932.2022.2140470>
40. Omar, M., Massawe, B. H., Shitindi, M. J., Pedersen, O., Meliyo, J. L., & Fue, K. G. (2024). Assessment of salt-affected soil in selected rice irrigation schemes in Tanzania: Understanding salt types for optimizing management approaches. *Frontiers in Soil Science*, 4, 1372838. <https://doi.org/10.3389/fsoil.2024.1372838>
41. Radanova, S. S. (2023). Plants in the national symbolism of European countries: A Link among countries, cultures, and religions. *Asian Journal of Research in Botany*, 6(2), 158-171. <http://geographical.openuniversityarchive.com/id/eprint/1381>
42. Saminadane, T., Geddam, S., Krishnaswamy, P., Jothiganapathy, K., Tamilselvan, A., Ramadoss, B. R., Singh, U. S., Singh, R. K., Platten, J. D., Gregorio, G. B., Singh, N. K., Bisht, D. S., Kota, S., Ponnuvel, S., & Guntupalli, P. (2024). Development of early maturing salt-tolerant rice variety KKL(R) 3 using a combination of conventional and molecular breeding approaches. *Frontiers in Genetics*, 14, 1332691. <https://doi.org/10.3389/fgene.2023.1332691>
43. Samota, M. K., Awana, M., Krishnan, V., Kumar, S., Tyagi, A., Pandey, R., ... & Singh, A. (2024). A novel micronutrients and methyl jasmonate cocktail of elicitors via seed priming improves drought tolerance by mitigating oxidative stress in rice (*Oryza sativa* L.). *Protoplasma*, 261(3), 553-570. <https://doi.org/10.1007/s00709-023-01914-x>
44. Senthilkumar, K., Sillo, F. S., Rodenburg, J., Dimkpa, C., Saito, K., Dieng, I., & Bindraban, P. S. (2021). Rice yield and economic response to micronutrient application in Tanzania. *Field Crops Research*, 270, 108201. <https://doi.org/10.1016/j.fcr.2021.108201>
45. Susanti, W. I., Cholidah, S. N., & Agus, F. (2024). Agroecological nutrient management strategy for attaining sustainable rice self-sufficiency in Indonesia. *Sustainability*, 16(2), 845. <https://doi.org/10.3390/su16020845>
46. Suvi, W. T., Shimelis, H., Laing, M., Mathew, I., & Shayanowako, A. I. (2021). Variation among Tanzania rice germplasm collections based on agronomic traits and resistance to rice yellow mottle virus. *Agronomy*, 11(2), 391. <https://doi.org/10.3390/agronomy11020391>
47. technologies. *Water*, 15(10), 1802. <https://doi.org/10.3390/w15101802>
48. Wen, Y., Ma, Y., Wu, Z., Yang, Y., Yuan, X., Chen, K., ... & Sun, Y. (2024). Enhancing rice ecological production: synergistic effects of wheat-straw decomposition and microbial agents on soil health and yield. *Frontiers in Plant Science*, 15, 1368184. <https://doi.org/10.3389/fpls.2024.1368184>
49. Yobebe, A. B. (2021). Interaction of soil-inorganic nitrogen in rice fields of Kilombero floodplain, Tanzania. *International Journal of Bonorowo Wetlands*, 11(1). <https://doi.org/10.13057/bonorowo/w110104>
50. Zamora Re, M. I., Tomasek, A., Hopkins, B. G., Sullivan, D. M., & Brewer, L. (2022). Managing salt-affected soils for crop production (PNW 601; Rev. ed.). Oregon State University Extension Service. <https://extension.oregonstate.edu/pub/pnw-601>



51. Zhang, K., Khan, M. N., Luo, T., Bi, J., Hu, L., & Luo, L. (2024). Seed priming with gibberellic acid and ethephon improved rice germination under drought stress via reducing oxidative and cellular damage. *Journal of Soil Science and Plant Nutrition*, 1-15. <https://doi.org/10.1007/s42729-024-01691-3>
52. Zhang, R., Wang, Y., Hussain, S., Yang, S., Li, R., Liu, S., Chen, Y., Wei, H., Dai, Q., & Hou, H. (2022). Study on the effect of salt stress on yield and grain quality among different rice varieties. *Frontiers in Plant Science*, 13, 918460. <https://doi.org/10.3389/fpls.2022.918460>
53. Zhu, W., Gu, S., Jiang, R., Zhang, X., & Hatano, R. (2024). Saline–alkali soil reclamation contributes to soil health improvement in China. *Agriculture*, 14(8), 1210. <https://doi.org/10.3390/agriculture14081210>