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Chitosan–Alginate Seed Encrusting Enhances Salt Tolerance in Sweet Corn

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ABSTRACT

Soil salinity is one of the most critical factors limiting global crop productivity, significantly hampering seed germination and early seedling development. This study examined the effects of seed treatment with chitosan and sodium alginate (NaAlg) on seedling growth and physiological responses of sweet corn (*Zea mays* L. *saccharata*) under different salinity conditions. The experiment was arranged as a two-factor factorial in a completely randomized design with three repetitions. The first factor involved bio-based treatments (untreated control, 0.5% chitosan, 0.75% chitosan, 1% NaAlg, and 1.5% NaAlg). The second factor included four salinity levels (0, 25, 50, and 100 mM NaCl) in pot setups. Results showed that seed treatment with 0.5% chitosan significantly increased seedling emergence percentage and rate while decreasing emergence time, mainly by improving biochemical and ionic properties. Notably, encrusted seeds accumulated higher levels of proline and soluble sugars, aiding osmotic adjustment and energy supply during early growth. Additionally, lower levels of H_2O_2 and MDA indicated decreased oxidative stress, while higher chlorophyll content maintained photosynthetic capacity. Nutrient analysis revealed increased uptake of N, P, and K^+ and reduced Na^+ accumulation, indicating better ion balance. These biochemical and physiological improvements led to higher seedling vigor compared to untreated seeds, which experienced nutrient loss, increased Na^+ toxicity, and disrupted metabolism. Overall, these findings suggest that seed treatment with chitosan and NaAlg improves salinity tolerance in sweet corn. By coordinating osmoprotectants, antioxidant defenses, and nutrient regulation, ultimately enhancing seedling establishment in saline soils.

1 | Introduction

Salinity is a major abiotic stressor that negatively impacts all stages of plant growth and development, from germination to biomass accumulation, grain, and fruit production, especially in arid and semi-arid regions (Zorb et al. 2019; Ben Gaied et al. 2024). Among these stages, seed germination is particularly sensitive and vital because it sets the stage for subsequent growth. Damage at this early stage is often irreversible, and in many farming systems, seeds are frequently exposed to salinity stress precisely during germination. In saline and dry soils, germination and early seedling establishment are widely recognized as the most vulnerable growth stages (Xie et al. 2019). High salt levels lower osmotic potential and create unfavorable physiological conditions, leading to significant reductions in seedling emergence and vigor. Physiological responses to salinity include decreases in turgor pressure, inhibition of photosynthetic activity, and disruption of cellular metabolism (Khan et al. 2022). The build-up of salts in the soil solution decreases water uptake, further slowing germination rates and hindering early growth.

Sweet corn (*Zea mays var. saccharata*), a member of the Gramineae family, originated from a mutation at the SU locus

on chromosome 4 of normal maize. This mutation causes sugars and water-soluble polysaccharides to build up in the endosperm, giving sweet corn its distinctive flavor and texture (Sidahmed et al. 2025; Behboud et al. 2024). The crop is primarily grown for its edible kernels. It has significant agricultural value, ranking second among vegetables for processing methods like canning and freezing, and fourth for fresh consumption (Mhike et al. 2012; Kannaujia et al. 2019). Despite its commercial importance, sweet corn is moderately sensitive to salinity (threshold EC ≈ 3.7 dS/m), and increasing electrical conductivity in irrigated fields increasingly threatens seed germination and seedling establishment. These early-stage issues caused by osmotic stress and ionic toxicity are significant limitations to successful cultivation (Shi et al. 2025).

Numerous studies have confirmed the harmful effects of salinity on the germination of maize and sweet corn. Shah et al. (2021) reported that salinity stress significantly lowered germination percentage, germination energy, seedling vigor, and biomass in maize. Similarly, Shetereva et al. (2015) found that salinity reduced both the rate and the percentage of germination in sweet corn, while increasing levels of malondialdehyde (MDA) and proline, markers of oxidative stress. In another study, Padilha et al. (2024) observed that alpha-amylase activity, a key enzyme for seed reserve mobilization, decreased under rising salinity stress. Given the increasing severity of soil salinity and its harmful effects on early crop growth, there is an urgent need for practical, low-cost strategies to improve salinity tolerance during germination. One promising approach is seed priming, a pre-sowing technique that prepares seeds to withstand suboptimal environmental conditions. Seed priming has been shown to enhance the germination rate, seedling vigor, nutrient uptake, and ultimately crop yield under stress conditions (Khalequzzaman et al. 2023).

Among various priming agents, chitosan, a natural biopolymer, has recently gained significant attention. Chitosan is a positively charged, biodegradable, non-toxic polysaccharide derived from the N-deacetylation of chitin, and it is the second most abundant polysaccharide in nature after cellulose (Sen and Das 2024). Its structural and chemical properties enable it to serve as a powerful elicitor, boosting plant resistance to salinity and drought stress by increasing water uptake, antioxidant defenses, and metabolic balance (Rehman et al. 2024).

Growing research supports the beneficial effects of chitosan on seed germination and seedling growth under saline conditions. For example, Hameed et al. (2014) demonstrated that 0.2% chitosan improved germination traits and shortened the average germination time in wheat under saline environments. Mansouri and Omidi (2018) noted that 0.08% chitosan significantly increased shoot length and germination percentage in quinoa. Behboud and Moradi (2022) observed the highest germination rate with 0.5% chitosan compared to the control, while Khalesro et al. (2016) reported that 2% chitosan resulted in the best seedling growth for Dragonhead (*Dracocephalum moldavica* L.) and savory (*Satureja hortensis* L.) plants. Furthermore, chitosan nanoparticles have been shown to elevate proline, catalase, and superoxide dismutase levels in barley (Behboudi et al. 2018) and to enhance photosynthetic pigment concentrations in tomatoes under saline conditions (Attia et al. 2021).

Although promising results have been observed across various crops, few studies have investigated the interactive effects of chitosan and salinity stress on sweet corn germination and biochemical responses, particularly under controlled conditions. This knowledge gap is significant due to the crop's economic importance and its sensitivity to salinity. Therefore, this study aims to examine the combined effects of different chitosan concentrations and salinity levels on sweet corn's germination performance and biochemical traits. The results are expected to help develop effective seed enhancement strategies, improve early-stage stress tolerance, and promote more sustainable sweet corn production in saline-affected areas.

2 | Materials and Methods

2.1 | Experimental Design

The experiment employed a two-factor factorial with a completely randomized design and three Replications. The first factor included five levels: untreated (control), chitosan 0.5%, chitosan 0.75%, NaAlg 1%, and NaAlg 1.5%. The second factor included four NaCl concentrations (0, 25, 50, and 100 mM) to impose salinity stress. Each combination was replicated three times, giving a total of 60 (5 × 4 × 3) experimental units (pots).

2.2 | Experimental Method

For the experiment, potting soil—a 2:1 mixture of field soil and soft sand—was autoclaved at 120°C for 2 h. Then, 80 nylon pots (25 cm tall and 18 cm in diameter) were filled, with the soil surface 5 cm below the rim. Twenty seeds were sown per pot at a depth of 2.5–3 cm. Pots were irrigated every 5 days with either distilled water or a sodium chloride solution, depending on their treatment group. To prevent salt buildup, all pots were drained and rinsed with distilled water weekly. The number of established seedlings was counted daily for 3 weeks. At the five-leaf stage, five seedlings were randomly selected for measuring the desired indicators.

2.3 | Evaluation of Germination Indices

The following indices were measured: Seedling emergence percentage (SEP), seedling emergence rate (SER), and mean emergence time (MET) were calculated using the equations described below.

$$\mathrm{SEP} = n / N \times 100 \tag{1}$$

where n is the total number of grown seedlings after 21 days, and N is the number of planted seeds.

$$\mathrm{SER} = \sum n_i / D_i \tag{2}$$

$$\mathrm{SEM} = \left(\sum D \times N \right) / \left(\sum N \right) \tag{3}$$

where n_i is the number of seedlings grown, and D_i is the number of the corresponding growing days.

2.4 | Determination of Biochemical Parameters in Leaf Tissue

Total soluble sugar content was measured following the protocol of Irigoyen et al. (1992) using the anthrone reagent method. Briefly, the extracted samples were reacted with an anthrone-sulfuric acid solution, along with glucose standards. The absorbance of the resulting green complex was spectrophotometrically measured at 650 nm. The concentration of soluble sugar in the samples was then determined.

Proline concentration in leaf samples was measured using the method described by Paquin and Lechasseur (1979). A calibration curve was created with serial dilutions of L-proline as a standard. Absorbance readings for both the standards and the extracted samples were taken at 515 nm with a UV spectrophotometer (Shimadzu 54A, Japan). The proline content in the plant tissue was then calculated from the standard curve.

Malondialdehyde (MDA) content, an indicator of membrane lipid peroxidation, was measured following the method described by Heath and Packer (1968). Fresh leaf samples (0.2 g) were homogenized in trichloroacetic acid (TCA) solution and centrifuged. The supernatant was then reacted with thiobarbituric acid (TBA), and the absorbance of the mixture was measured at 532 and 600 nm. The MDA concentration was calculated using an extinction coefficient of 155 $mM^{-1} cm^{-1}$.

Hydrogen peroxide (H_2O_2) content was measured spectrophotometrically following the method described by Alexieva et al. (2001). The reaction mixture included 0.5 mL of supernatant from leaf extracts homogenized in 0.1% trichloroacetic acid (TCA), 0.5 mL of 100 mM potassium phosphate buffer (pH 7.0), and 2 mL of 1 M potassium iodide (KI) prepared in fresh double-distilled water. A blank was prepared with 0.1% TCA without leaf extract. The mixture was incubated in the dark for 1 h, and the absorbance was measured at 390 nm using a UV spectrophotometer.

2.5 | Measurement of Leaf Chlorophyll Content

Chlorophyll was extracted from plant leaves using 80% acetone and calcium carbonate in an ice bath. The amount of chlorophyll in the leaves was measured following the method suggested by Arnon (1949). For this process, 0.5 g of freshly crushed leaves was placed in a porcelain mortar. Then, 10 mL of cold 80% acetone was added in two portions, along with 0.5 g of calcium carbonate powder. The mortar was kept in an ice bath, and the leaf samples were ground in a low-light environment until a completely uniform, homogeneous mixture was obtained, ensuring that all chlorophyll was extracted from the leaf tissue. The mixture was then poured into specialized centrifuge tubes and spun at 3000 rpm for 15 min at low temperature. The supernatant was collected, and its absorbance was measured at 663, 645, and 470 nm using a UV spectrophotometer (SHIMADZU 54, Shimadzu, Dubai, UAE).

2.6 | Measurement of Elemental Contents

2.6.1 | Measurement of Nitrogen and Phosphorus Content

Leaf nitrogen concentration was determined following the procedure described by Novamsky et al. (1974). Fresh leaf samples were first dried in an oven at 78°C for approximately 48 h. The dried material was then subjected to sequential digestion on a heating block set to 180°C using sulfuric acid, salicylic acid, and hydrogen peroxide. Subsequently, the absorbance of nitrogen in the digested samples was measured at 660 nm with a UV spectrophotometer. A regression line derived from standard solutions of known concentration was used to calculate the nitrogen concentration. Finally, the nitrogen content was determined by interpolating the sample absorbance onto this standard curve. Phosphorus content was determined using a colorimetric method involving the formation of a yellow vanadate-molybdate complex. The absorbance of this complex was measured at 420 nm with a UV spectrophotometer, and the phosphorus concentration was calculated (Sacala et al. 2016).

2.6.2 | Measurement of Potassium and Sodium Content

In this method, the ground plants were dried in an oven. Next, 1 g of a dry sample (seedling) was transferred to ceramic vessels and slowly heated to 500°C over 5 h in the oven. The final product was a white ash. The ash was cooled to room temperature, then 20 mL of 1 N hydrochloric acid (HCl) was added to each sample, followed by heating on a sand bath for 30 min. The samples were then diluted into a 100 mL volumetric flask. After preparing the plant extracts, the concentrations of potassium and sodium were measured using a flame photometer (PFP7-England) (Peng et al. 2004).

2.7 | Statistical Analysis

Data analysis was performed using SAS (version 9.4), and graphs were created in Excel (2013). The means of the main effects were compared using Duncan's multiple-range test at a 5% significance level. When interactions were significant, the L.S. Means procedure was used to compare the means of the evaluated traits at the same significance level.

3 | Results and Discussion

3.1 | Seedling Emergence Percentage (SEP)

The results of the mean comparison for encrusting levels under different salinity stress conditions show that increasing salinity levels decrease SEP. Under non-saline conditions, the highest SEP (100%) was achieved with encrusting using 0.5% chitosan, 0.75% chitosan, 1% NaAlg, and 1.5% NaAlg, while the lowest SEP (95%) was in the control treatment. At 25 mM salinity stress, the highest SEP (95%) occurred in seeds encrusted with 0.5% chitosan, whereas the lowest (80%) was in the control treatment. No significant difference was observed

between 0.5% chitosan and 1.5% NaAlg treatments. At a salinity level of 50 mM NaCl, all seed-encrusting treatments, including chitosan (0.5% and 0.75%) and NaAlg (1% and 1.5%), resulted in a statistically significant increase in SEP, with a 15% improvement compared to the untreated treatment. However, under severe salinity stress (100 mM NaCl), a more differentiated response pattern was observed. The 0.5% chitosan treatment was identified as the most effective, achieving the highest SEP of 90% and being statistically superior to all other treatments. Following that, the 0.75% chitosan treatment recorded an ASEP of 83%, while both NaAlg (1% and 1.5%) treatments achieved 70%. These values represent increases of 25%, 18%, and 5%, respectively, compared to the untreated control under the same salinity level (Table 1).

3.2 | Seedling Emergence Rate (SER)

The results of the mean comparison showed that as salinity stress levels increased, the SER of sweet corn decreased, although the decline was less noticeable in seeds encrusted with compounds. Under non-saline conditions, the highest SER was achieved with 0.5% chitosan treatment (18.55 seed day^{-1}), while the lowest was in the control treatment (16.17 seed day^{-1}). At 25 mM salinity stress, seeds encrusted with 0.5% chitosan showed the highest SER, which was significantly greater than other encrusting treatments. At 50 and 100 mM salinity stress, the highest SER was observed in seeds encrusted with 0.5% chitosan, with mean values of 9.86 and 6.44 seed day^{-1}, respectively, while the lowest rates were found in the control treatment.

3.3 | Mean Emergence Time (SET)

The mean comparison of the data showed that, as salinity stress increased, the SET also increased. At all four levels of salinity stress, the highest SET was recorded in the control treatment, while the lowest was obtained from seeds encrusted with 0.5% chitosan. Encrusting treatments, in general, reduced the SET of seedlings compared with the untreated treatment (Table 1).

3.4 | Soluble Sugar Content

The results of the mean comparison for different encrusting levels under each salinity stress condition showed that at 0, 25, 50, and 100 mM salinity, the highest leaf soluble sugar contents were observed with 0.5% chitosan treatment, with mean values of 25.86, 27.23, 30.41, and 33.77 mg g^{-1} FW, respectively. The lowest contents were recorded in the control treatment, with mean values of 13.63, 17.57, 21.05, and 33.77 mg g^{-1} FW, respectively (Figure 1).

TABLE 1 | Mean comparison of chitosan and NaAlg treatment on emergence indices of sweet corn under salinity stress in greenhouse conditions.

Salinity (mM)	Encrusting compound	SEP (%)	SER (seedling day^{-1})	SET (day)
0	Untreated (Control)	95 b	16.17 b	1.54 i
	Chitosan 0.5%	100 a	18.55 a	1.16 k
	Chitosan 0.75%	100 a	18.26 a	1.31 jk
	NaAlg 1%	100 a	17.68 a	1.31 jk
	NaAlg 1.5%	100 a	17.52 a	1.50 ij
25	Untreated (Control)	80 f	10.84 fg	2.85 e
	Chitosan 0.5%	95 b	14.83 c	1.89 h
	Chitosan 0.75%	85 d	12.43 de	2.29 g
	NaAlg 1%	90 b	13.50 d	1.98 h
	NaAlg 1.5%	85 d	11.64 ef	2.59 f
50	Untreated (Control)	75 g	4.61 lm	4.26 a
	Chitosan 0.5%	90 c	9.86 gh	3.15 d
	Chitosan 0.75%	90 c	9.06 hi	3.38 c
	NaAlg 1%	90 c	8.08 ij	3.76 b
	NaAlg 1.5%	90 c	7.27 jk	4.21 a
100	Untreated (Control)	65 i	3.65 m	4.33 a
	Chitosan 0.5%	90 a	6.44 k	3.49 c
	Chitosan 0.75%	83 e	5.33 l	4.19 a
	NaAlg 1%	70 h	4.17 m	3.93 b
	NaAlg 1.5%	70 h	4.06 m	4.28 a

Note: According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

3.5 | Proline Content

Across all four salinity levels, applying different encrusting treatments (chitosan and NaAlg) increased proline content. However, the positive effects of 0.5% chitosan, followed by 0.75% chitosan, were more significant than those of NaAlg. As shown in Figure 2, under 0 mM salinity stress, the highest proline content (4.69 μmol g^{-1} FW) was observed with 0.5% chitosan, and the lowest (1.09 μmol g^{-1} FW) was recorded in the control treatment. No significant differences were observed between encrusting treatments with 1% and 1.5% NaAlg. Similarly, under 25 mM salinity stress, the highest proline content (5.36 μmol g^{-1} FW) was observed with 0.75% chitosan treatment, and the lowest value (1.31 μmol g^{-1} FW) was observed in the control treatment. At 50 and 100 mM salinity levels, the highest proline content was again observed in the 0.5% chitosan-encrusted treatment, while the lowest was observed in the control treatment (Figure 2).

3.6 | Malondialdehyde (MDA) Content

According to the mean-comparison results, MDA content increased with increasing salinity stress. However, encrusting treatments decreased MDA accumulation compared to the control treatment. At all salinity stress levels, the highest MDA content was recorded in the control treatment, while the lowest was in seeds treated with 0.5% chitosan. At 25 mM salinity stress, there was no significant difference between 0.75% chitosan and 1% NaAlg (Figure 3).

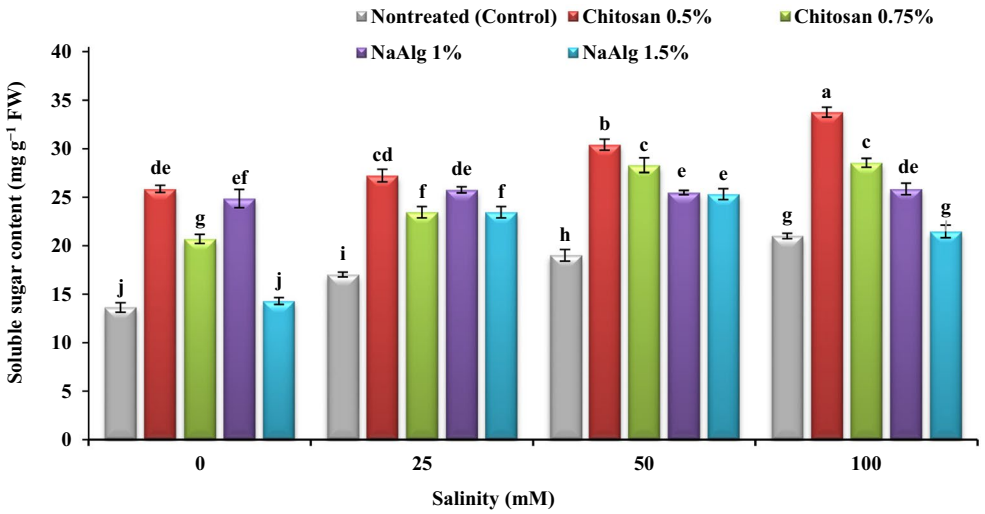

FIGURE 1 | Mean comparison of chitosan and NaAlg treatment on soluble sugar content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

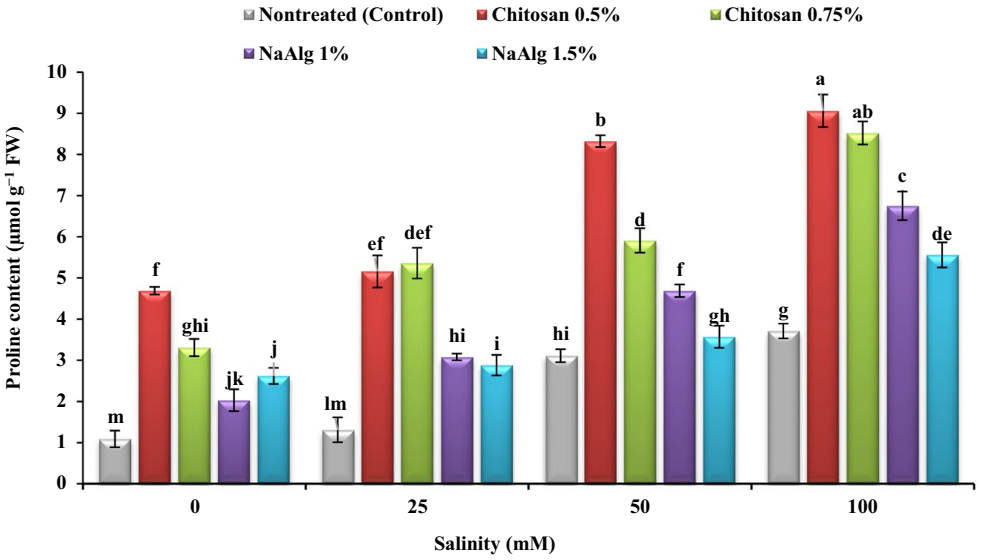

FIGURE 2 | Mean comparison of chitosan and NaAlg treatment on proline content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

3.7 | Hydrogen Peroxide (H_2O_2) Content

The results indicated that salinity stress triggered a significant accumulation of H_2O_2, whereas seed encrusting effectively suppressed this oxidative burst. In the control treatment, H_2O_2 levels rose sharply with increasing salinity, reaching a maximum at 100 mM NaCl. However, the exogenous application of 0.5% Chitosan consistently maintained the lowest H_2O_2 levels across all salinity increments, significantly reducing oxidative damage compared to the control treatment (Figure 4).

3.8 | Total Chlorophyll Content

The results demonstrated that salinity stress significantly reduced photosynthetic pigments, whereas the application of chitosan and NaAlg significantly ameliorated this effect. Under non-stress conditions (0 mM NaCl), the highest total chlorophyll levels were observed in plants treated with 0.5% Chitosan, followed by 1% NaAlg, both of which were significantly superior to the nontreated control. As salinity increased to 100 mM, a substantial and steady decline in chlorophyll content was evident in the control treatment, reaching its minimum at the highest stress level. Conversely, the application of 0.5% Chitosan consistently maintained the highest chlorophyll concentrations across all salinity levels (0, 25, 50, and 100 mM), effectively mitigating the degradative impact of salt stress. Notably, the lower concentrations of the tested biopolymers (0.5% Chitosan and 1% NaAlg) were more effective in preserving chlorophyll than the higher concentrations (0.75% Chitosan and 1.5% NaAlg), which occasionally showed values closer to the control treatment under high salinity (Figure 5).

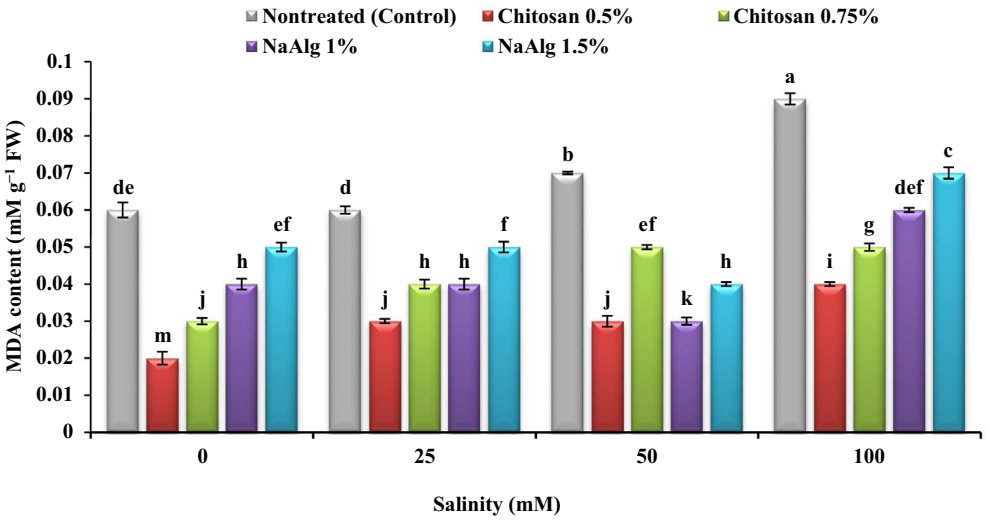

FIGURE 3 | Mean comparison of chitosan and NaAlg treatment on MDA content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

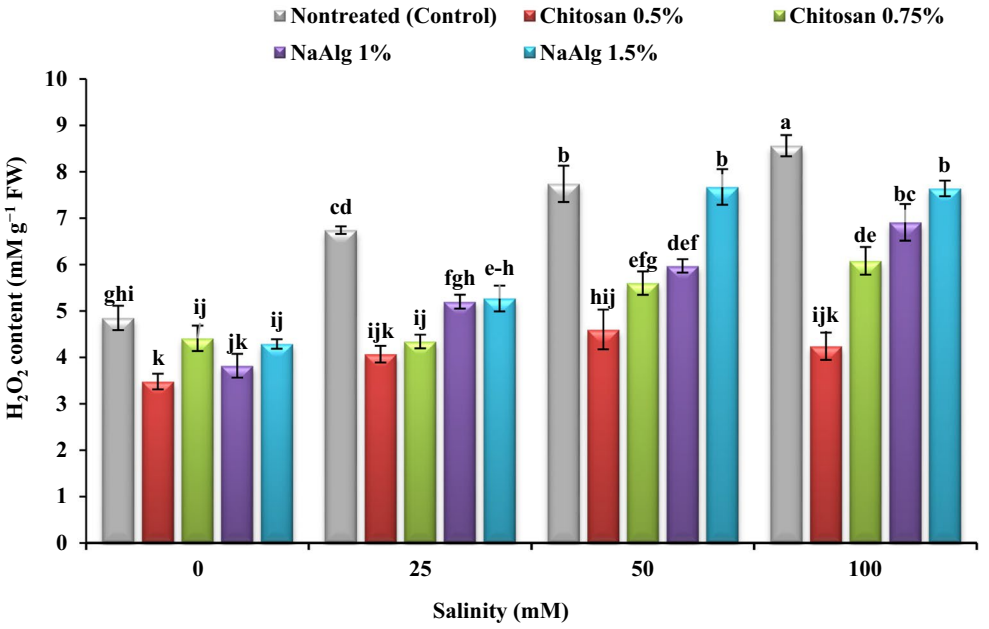

FIGURE 4 | Mean comparison of chitosan and NaAlg treatment on H_2O_2 content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

3.9 | Nitrogen Content

The results for nitrogen content revealed that increasing salinity levels exerted a significant inhibitory effect on nitrogen accumulation, whereas treatments with chitosan and NaAlg effectively alleviated this reduction. Under control conditions (0 mM NaCl), the highest nitrogen levels were observed in plants treated with 0.5% Chitosan and 1% NaAlg, both of which showed a significant increase compared to the control. As salinity stress increased to 100 mM NaCl, a progressive decline in nitrogen concentration was observed across all treatments, with the greatest reduction in the control. However, the application of 0.5% Chitosan consistently resulted in the highest nitrogen retention across all salinity levels, significantly outperforming the control group even under severe stress (100 mM NaCl) (Figure 6).

3.10 | Phosphorus Content

The results showed that as the NaCl concentration increased to 100 mM, a sharp decline in phosphorus levels was observed in the control treatment, reaching its minimum at the highest salinity. Under non-saline conditions, the application of 0.5% chitosan resulted in the highest phosphorus content (13.04 mg g^{-1} FW) among all seed encrusting treatments, significantly surpassing the control. This value represents a 37% increase compared to the lowest

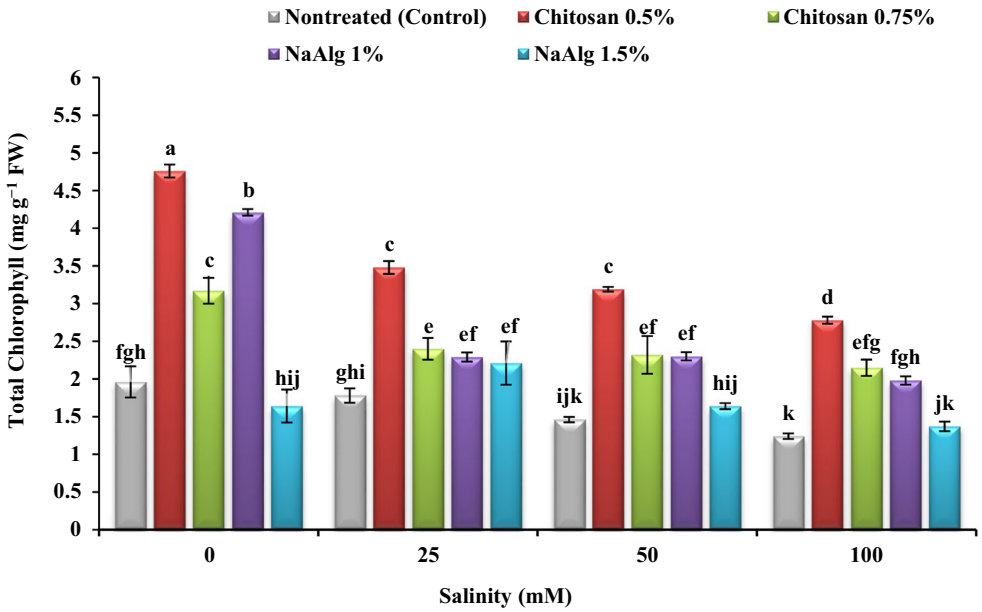

FIGURE 5 | Mean comparison of chitosan and NaAlg treatment on Total Chlorophyll content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

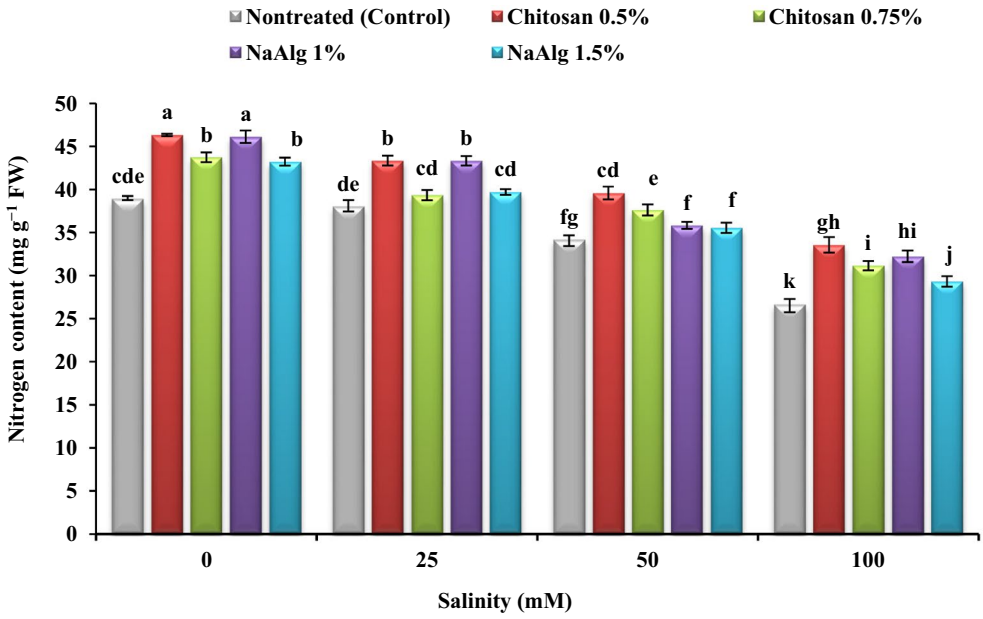

FIGURE 6 | Mean comparison of chitosan and NaAlg treatment on nitrogen content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

phosphorus content observed in the control treatment (8.25 mg g^{-1} FW). At salinity levels of 25, 50, and 100 mM, the highest phosphorus contents (10.53, 9.50, and 8.00 mg g^{-1} FW, respectively) were again found in the 0.5% chitosan treatment (Figure 7).

3.11 | Potassium (K^+) Content

The results showed that K^+ content in plant tissues varied significantly, influenced by both salinity stress and encrusting treatments. Under non-saline conditions (0 mM NaCl), the highest K^+ accumulation was observed in plants treated with 0.5% Chitosan, which significantly outperformed the control. As salinity levels increased from 25 to 100 mM NaCl, a progressive decline in K^+ content was observed across all experimental units; however, the magnitude of this reduction was markedly less pronounced in plants receiving encrusting treatments. Specifically, 0.5% Chitosan consistently maintained superior potassium levels compared to other treatments at every salinity increment, followed by 1.5% NaAlg (Figure 8).

3.12 | Sodium (Na^+) Content

Mean comparisons revealed a progressive increase in Na^+ content with increasing salinity, whereas seed-encrusting treatments mitigated Na^+ accumulation relative to the control. Across all salinity regimes, the highest Na^+ concentrations

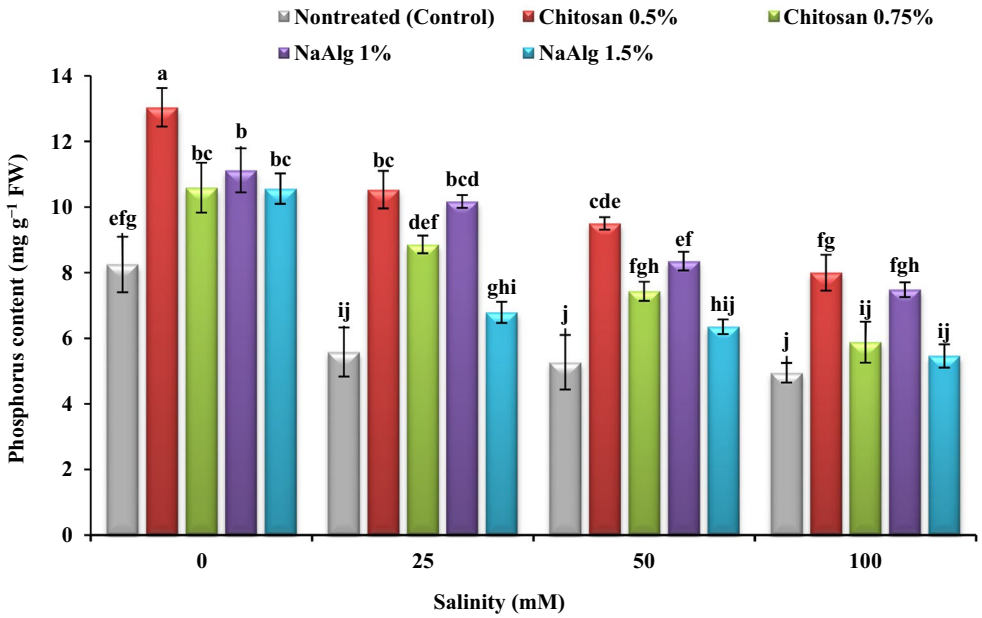

FIGURE 7 | Mean comparison of chitosan and NaAlg treatment on phosphorus content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

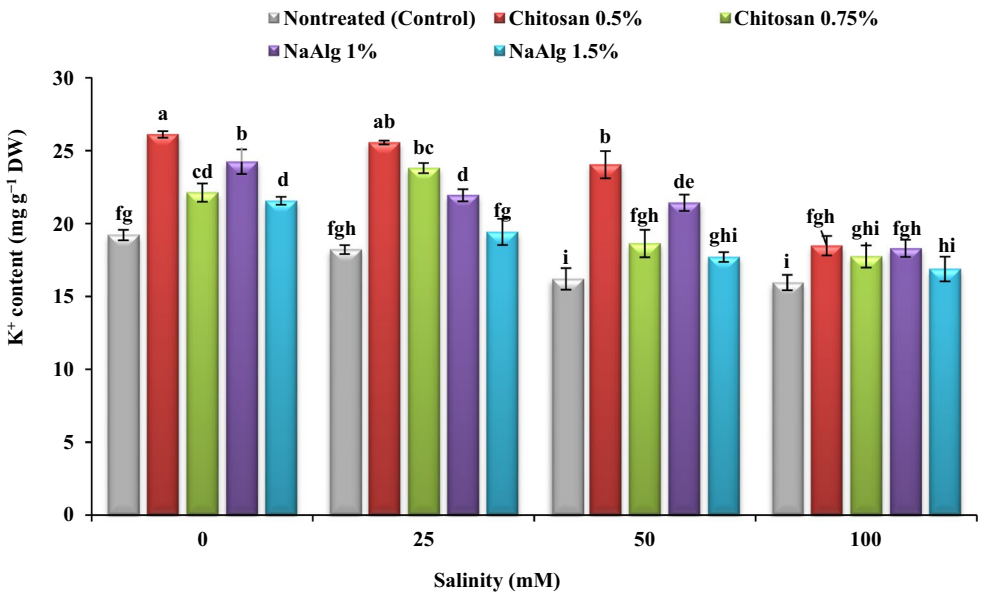

FIGURE 8 | Mean comparison of chitosan and NaAlg treatment on K^+ content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

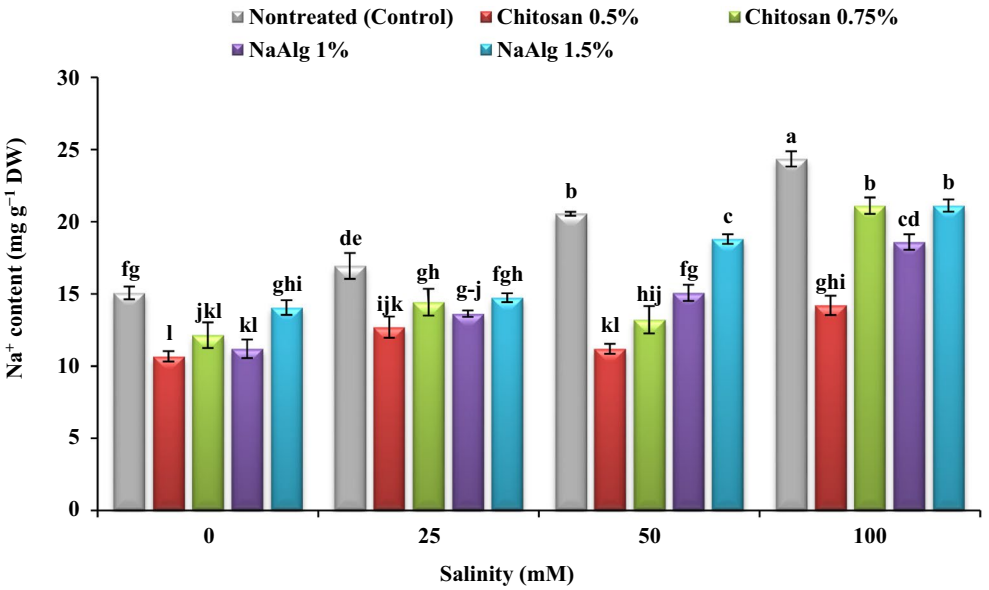

FIGURE 9 | Mean comparison of chitosan and NaAlg treatment on Na^+ content of sweet corn under salinity stress in greenhouse conditions. According to Duncan's multiple range test, means with the same letter are not significantly different at the 5% level.

were consistently recorded in the control treatment, whereas the lowest were observed in seeds encrusted with 0.5% chitosan. Under non-saline conditions, there was no significant difference between the 0.5% chitosan and 1% NaAlg treatments (Figure 9).

Principal component analysis (PCA) was performed to clarify the relationship between seedling establishment indices and the physiological and biochemical changes in primed sweet corn seeds. The first two principal components (PC1 and PC2) accounted for 72.5% and 14.4% of the total variance, respectively. The biplot showed a positive correlation among sodium (Na^+) ion accumulation, malondialdehyde (MDA) content, and hydrogen peroxide (H_2O_2) levels. Conversely, these traits displayed strong negative correlations with Cht content. An increase in Na^+ results in higher levels of MDA and H_2O_2 and a decrease in Cht content. Elevated N, P, and K^+ levels positively impact SEP and SER but negatively influence the MDA MET trait (Figure 10).

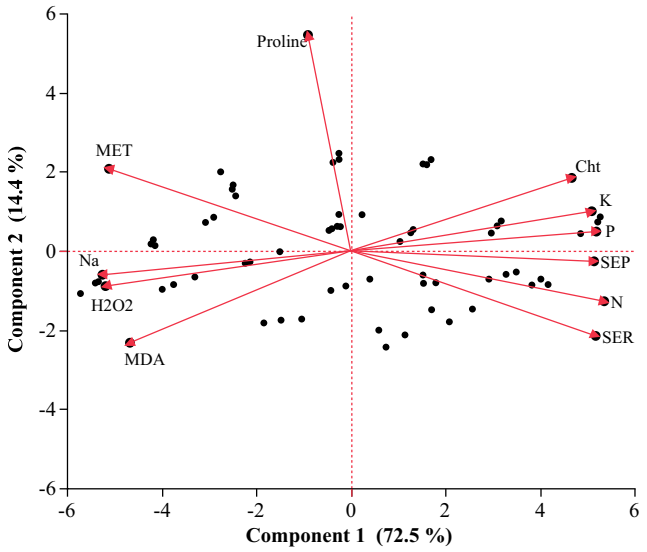

FIGURE 10 | Principal component analysis for seedling indices and some biochemical and Na^+ and K^+ content in sweet corn seedlings under priming treatment and salinity stress. Cht, chlorophyll; MDA, malondialdehyde, MER, mean emergence time; SEP, seedling emergence percentage; SER, seedling emergence rate.

4 | Discussion

We demonstrated that seed treatment with biopolymers, especially 0.5% chitosan, significantly improved emergence traits, biochemical responses, antioxidant capacity, and nutrient balance in sweet corn under salinity stress. Treated seedlings showed higher emergence percentage and rate, shorter average emergence time, increased biomass, higher chlorophyll content, and lower Na^+ accumulation. These improvements collectively suggest that seed treatment activates multiple defense pathways that work together to support seedling establishment under stress.

Seed treatment appears to improve germination and seedling growth, especially rootlet development under saline conditions, helping reduce the harmful effects of salt toxicity and physiological drought. As a result, treated seeds showed higher germination rates and quicker emergence than the control. Although salinity stress lowered germination in all treatments, the decline was less in encrusted seeds, consistent with results in wheat, maize, and other crops (Ashraf and Foolad 2007; Bakht et al. 2011; Feghhenabi et al. 2020). Mechanistically, faster germination is associated with increased activity of hydrolytic enzymes such as α-amylase, improved bioenergetic status with greater ATP production, and more efficient RNA and DNA synthesis, allowing seedlings to emerge earlier and initiate photosynthesis sooner (Guzman-Ortiz et al. 2019; Wunthunyarat et al. 2020).

The accumulation of soluble sugars and proline was significantly higher in primed seedlings, aiding in osmotic regulation,

maintaining cell turgor, and stabilizing proteins and membranes. This agrees with other studies showing that osmolyte buildup under salinity helps protect photosynthesis (Savvas and Ntatsi 2015; Silva et al. 2003). Notably, in our research, higher osmolyte levels were associated with lower oxidative stress, indicating a coordinated mechanism in which osmotic regulation and ROS detoxification support each other. Salinity stress increased MDA and H_2O_2, markers of lipid peroxidation and ROS accumulation, but treated seedlings showed much lower levels. Previous studies found that chitosan boosts the antioxidant system, reducing ROS toxicity (Fedina et al. 2009; Sheweita et al. 2023). The correlation analysis further confirms these findings by showing that seedling indicators, including SEP and SER, are strongly influenced by element and Cht characteristics. These parameters showed strong positive relationships with N, P, and K^+ levels, suggesting that nutrient accumulation supports germination and seedling growth by protecting tissues from oxidative damage. Conversely, SEP and SER showed strong negative correlations with Na^+ content, MDA, and H_2O_2 levels (Figure 11). By stabilizing membranes and reducing oxidative stress, treated seedlings maintained cellular integrity, thereby directly supporting nutrient absorption and chlorophyll synthesis. Therefore, ROS management is not a standalone effect but is vital in protecting photosynthesis and metabolic functions.

Salinity generally accelerates pigment degradation by increasing chlorophyllase activity, disrupting chloroplast ultrastructure, and diverting nitrogen to stress metabolites such as proline (Noreen and Ashraf 2009). Consistent with findings in mung bean and coffee (Ahmad et al. 2019; Dzung et al. 2011), priming with chitosan preserved chlorophyll *a*, chlorophyll *b*, and carotenoids, aiding in maintaining photosynthetic efficiency. Our results support the idea that antioxidant protection and osmotic adjustment work together to safeguard chloroplasts and ensure carbon assimilation under stress.

Nutrient analyses showed that encrusted plants retained higher levels of nitrogen, phosphorus, and potassium while

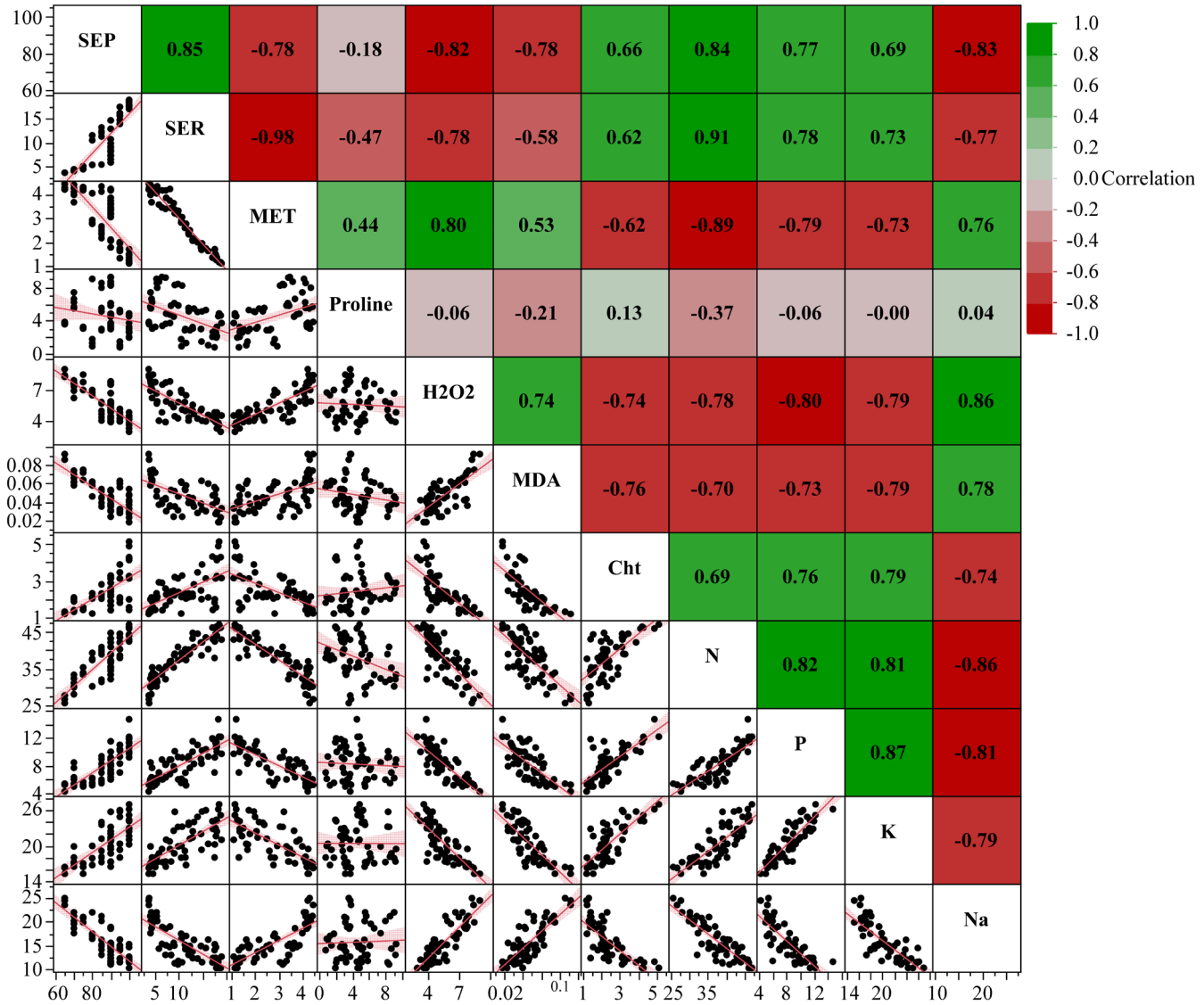

FIGURE 11 | Heat map correlation for seedling indices, biochemical content, and Na^+ and K^+ levels in sweet corn seedlings under priming treatment and salinity stress. Cht, chlorophyll; MDA, malondialdehyde; MER, mean emergence time; SEP, seedling emergence percentage; SER, seedling emergence rate.

decreasing sodium accumulation. Salinity often impairs N and P transport and reduces K^+ absorption due to Na^+ competition and membrane damage (El Sayed et al. 2019; Paul et al. 2023; Javed et al. 2024). Conversely, treated seedlings demonstrated improved root development and maintained selective ion uptake, reducing Cl^-/NO_3^- antagonism and balancing the K^+/Na^+ ratio (Theerakulpisut et al. 2016; Yun et al. 2018; Hadwiger et al. 2002).

Overall, these results show that seed priming activates multiple interconnected mechanisms that accelerate germination, osmolyte accumulation, ROS detoxification, pigment stability, and ion balance, thereby enhancing salinity tolerance. Unlike earlier work that focused on individual traits, our study reveals how these mechanisms are functionally connected, advancing understanding of priming as a systemic resilience strategy.

The experiments were limited to early seedling stages in controlled conditions, which may not capture the complexity of field environments. Additionally, while physiological and biochemical responses were measured, the underlying molecular and genetic pathways were not examined. Future research should employ transcriptomic and metabolomic profiling to explore how chitosan affects osmolyte synthesis, antioxidant enzymes, and ion transporters. It should also test performance across various genotypes and field settings.

From a practical standpoint, the findings highlight the potential of seed priming as an affordable, environmentally friendly method to enhance crop resilience. Combining priming with nutrient and water management can further improve crop establishment in saline soils. Applying this technique to other cereals and salt-sensitive crops could support sustainable food production amid the increasing global issue of soil salinization.

5 | Conclusion

This study shows that salinity stress significantly lowers sweet corn seedling indices in greenhouse conditions, with the lowest indices at the highest salinity levels. However, seeds treated with chitosan and NaAlg showed better seedling emergence, whereas untreated seeds had the slowest. As soil salinity increased, leaf sodium content rose considerably, while levels of potassium, nitrogen, and phosphorus declined. Overall, bio-based treatments like chitosan and NaAlg can improve seed establishment and enhance sweet corn seedling indices under salinity stress. Based on the effectiveness of 0.5% chitosan and 1% NaAlg in promoting seedling growth under varying salt stress levels, it is recommended to treat sweet corn seeds with these compounds in field conditions subject to salt stress.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data supporting the results are included in the article, and no additional source data is needed.

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