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Nano Zinc and Silicon Enhance Salinity Resilience in Sugar Beet (*Beta vulgaris*) Through Improved Sodium and Chloride Compartmentalization and Osmotic Regulation

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ABSTRACT

Soil salinity is a major abiotic stress that disrupts water uptake, ion homeostasis, carbohydrate metabolism, and organic acid accumulation of sugar beet (*Beta vulgaris* L.). Nano-fertilisers, due to enhanced mobility and reactivity, help plants in nutrient regulation, thus offering a promising strategy to mitigate such stresses. This study evaluates the comparative effects of zinc (Zn) and silicon (Si) nutrients as conventional and nano forms under salt stress and investigates their role at the cell and subcellular level in ion compartmentalization and osmotic regulation to mitigate salt stress in sugar beet. The experiment was conducted with three salinity levels (0, 75, and 150 mM NaCl), assessing ion distribution and regulation in the apoplast and symplast, two critical compartments for cellular ion transport and buffering of toxic ions. Nano Zn and Si significantly enhanced salt resistance by promoting sodium and chloride compartmentalization. At moderate salinity (75 mM NaCl), both nano Zn and nano Si reduced apoplastic and symplastic Na^+ contents by approximately 48% and 47%, respectively, compared to controls. K^+ retention improved markedly, with nano Si increasing apoplastic and symplastic K^+ by approximately 20% and 40% at moderate salinity levels (75 mM), respectively. While at a higher salinity level (150 mM NaCl), nano Zn and nano Si maintained significant reductions in Na^+ and Cl^- (around 45%–50%) and enhanced K^+ levels compared to controls, thereby contributing to improved osmotic regulation and ionic balance under salt stress. Enhanced accumulation of organic acids (malic, citric, oxalate) and sugars (sucrose, glucose, fructose) in both compartments under nano treatments reinforced the osmotic adjustment and helped plants to mitigate salt stress. These findings highlight the potential of nano zinc and silicon as effective agronomic tools for improving salinity tolerance in sugar beet under adverse conditions.

1 | Introduction

Soil salinity is one of the most critical abiotic stresses impacting global agriculture, currently affecting approximately 1.4 billion hectares, or 11% of the world's land area (FAO 2024a). Projections suggest that this affected area could increase to 24%–32% due to climate change, unsustainable agricultural irrigation practices, and seawater intrusion (FAO 2024b), threatening food security

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Summary

- Nano Zn and Si improve salt tolerance in sugar beet under stress.
- Nano fertilisers enhance sodium and chloride compartmentalization.
- Nano Si significantly increases potassium retention under salinity.
- Nano Zn and Si boost organic acid and sugar accumulation for osmotic regulation.
- Both nano fertilizers improve growth and physiological functions under salt stress.

globally. The economic consequences are equally severe, with the annual global cost of salt-induced land degradation in irrigated areas estimated at US$ 27.3 billion. Soil salinity stress disrupts ion homeostasis by interfering with the transport and distribution of ions, leading to ion imbalances, deficiency of essential nutrients, especially micronutrients (Arif et al. 2020), as well as osmotic stress due to high concentrations of Na^+ and Cl^- ions. These ions interfere with plant water uptake, lower soil water potential, induce physiological drought and osmotic stress, consequently impairing germination, growth, and overall plant development (Singh et al. 2025). As a result of these disturbances, photosynthesis, plant metabolism, and overall crop productivity are significantly reduced, even causing the death of plants (Pan et al. 2021).

Some plants like sugar beet (*Beta vulgaris* L.) and barley (*Hordeum vulgare* L.) have developed key strategies to cope with salt stress through specialised mechanisms. These include the partial substitution of K^+ with Na^+ for osmotic balance (Alavilli et al. 2023) and the use of Na^+/H^+ antiporter (BvNHX1) to sequester Na^+ into vacuoles, thereby preventing the cytoplasm (Adler et al. 2010). However, despite these adaptive mechanisms, these crops cannot withstand high levels of salinity. As the twenty-first century advances, agriculture is expected to evolve, with scientists moving away from a single-minded pursuit of genetic improvement toward a more integrated approach that combines it with other strategies. One of the key strategies to enhance salt tolerance is the effective management of plant nutrition, particularly through the use of nanofertilizers. Integrating nutrient management with salt-tolerant cultivars, efficient irrigation practices, and soil amendments can significantly improve plant productivity in salt-affected soils (Chhabra 2022). Nanofertilizers offer several advantages over conventional fertilisers, particularly under stress conditions. Due to their higher surface area, improved solubility, and targeted delivery, they enhance nutrient uptake, reduce losses, and lead to quicker physiological responses (Yadav et al. 2023). Nano nutrients also penetrate plant tissues more effectively and stimulate defence mechanisms, thereby further improving plant resilience, growth, and productivity in salt-affected soils (Singh et al. 2025).

The regulation of ions, sugars, and organic acids at the apoplast and symplast levels remains insufficiently understood. Addressing this gap is critical for improving fertiliser efficiency, enhancing nutrient management, and developing salt-tolerant crops. This research aims to fill this gap by investigating the effects of nano Zn and nano Si on ion regulation, sugar metabolism, and organic acid accumulation. By understanding how these nano fertilisers influence these processes, we can enhance crop performance under salinity stress, improve fertiliser use, and support agricultural productivity in salt-affected areas.

Building on this concept, our previous studies showed that nanoforms of zinc (Zn) and silicon (Si) have emerged as effective solutions to improve plant resilience under salinity stress (Shoukat, Pitann, Zafar, et al. 2024; Shoukat, Pitann, Hossain, et al. 2024). Despite the promising benefits of nanofertilizers, most existing research has primarily focused on their general effects on plant growth and stress tolerance. For instance, ZnO nanoparticles improved ion homeostasis and antioxidant activity in quinoa under salinity stress by enhancing K^+/Na^+ balance and reducing oxidative damage (Türkoğlu et al. 2024). Foliar application of silica nanoparticles has been shown to enhance the growth of sugar beet under combined salinity and saline irrigation stress by improving the K^+/Na^+ ratio, increasing antioxidant enzyme activity, and reducing oxidative stress (Alharbi et al. 2022). However, the precise roles of these nanoparticles in regulating ion balance, sugar metabolism, and organic acid accumulation, particularly in the apoplast and symplast at the cellular and subcellular levels, remain insufficiently studied (Shahzad et al. 2013).

This research aims to address this gap by investigating the comparative impacts of nano and conventional forms of Zn and Si on ion regulation, sugar metabolism, and organic acid accumulation in both the apoplast and symplast of sugar beet under different salinity conditions. The study will specifically examine how nano Zn and nano Si affect nutrient distribution, ion compartmentalization, and osmotic regulation, and how these changes contribute to enhanced salt tolerance and overall crop performance. It is expected that nano Zn will primarily reduce Na^+ accumulation in shoots, while nano Si will have a more significant regulatory effect in the roots. When combined, nano Zn and nano Si are anticipated to more effectively improve the compartmentalization of Na^+ and Cl^-, support osmotic adjustment, and maintain ion homeostasis, thus improving crop performance under salinity stress compared to their conventional forms.

2 | Materials and Methods

2.1 | Synthesis and Characterisation of Nanoparticles

Zinc oxide (ZnO) and silicon dioxide (SiO_2) nanoparticles (NPs) were synthesised through chemical methods to achieve high purity and nanoscale sizes. ZnO NPs were synthesised via a precipitation reaction. Zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) was used as the precursor, and sodium hydroxide (NaOH) was added as the base. The molar concentration of $Zn(NO_3)_2 \cdot 6H_2O$ was 0.1 M, and NaOH was added dropwise to maintain a reaction pH of 10. The reaction was carried out at room temperature (25°C) under constant stirring (300 rpm) for 2 h. The resulting precipitate was filtered, washed with deionised water, and dried at 60°C for 12 h. Finally, the ZnO NPs were calcined at 500°C for 2 h to improve crystallinity and particle structure (Chen et al. 2011). On the other hand, SiO_2 NPs were synthesised using the sol–gel method, employing tetraethyl orthosilicate (TEOS) as the precursor. A 0.1 M TEOS solution was prepared by dissolving TEOS in ethanol. The

molar ratio of TEOS to water was 1:4, and the catalyst used was ammonium hydroxide (NH_4OH) at a concentration of 0.01 M to adjust the pH to 9. The reaction mixture was stirred at 350 rpm at room temperature for 2 h. After gel formation, the mixture was aged for 24 h at room temperature. The gel was then filtered, washed with ethanol, and dried at 60°C for 12 h. Finally, the SiO_2 NPs were calcined at 550°C for 2 h to improve particle morphology and structural integrity (Azlina et al. 2016). Post-synthesis treatments, including agitation, drying, and calcination, were employed to optimise the particle morphology. The nanoparticles were characterised at Kiel University, Germany, using X-ray Diffraction (XRD), Ultraviolet–Visible (UV–Vis) Spectroscopy, and Scanning Electron Microscopy (SEM) to confirm their structure. Additional analysis with Transmission Electron Microscopy (TEM) revealed the particle size distribution, showing an average diameter of 12 nm for ZnO and 15 nm for SiO_2, consistent with nanoscale dimensions (Shoukat, Pitann, Hossain, et al. 2024).

2.2 | Experimental Framework

A controlled-environment experiment was conducted to assess the impact of NPs and conv. fertilisers on sugar beet growth under varying salinity stress levels. The experiment was conducted in growth chambers under a 14-h photoperiod, with a day/night temperature of 27°C/16°C and a relative humidity of 70%. Sugar beet seeds of the cultivar KWS Maradona were pre-soaked in a calcium sulfate solution to promote uniform germination before being transplanted into 5-L pots containing a modified Hoagland's nutrient solution. The nutrient solution in each pot was completely replaced three times per week (every 2–3 days) to ensure nutrient stability and prevent salt accumulation. The experiment included a control group (nutrient solution only) and treatments supplemented with nano ZnO and SiO_2 (10 ppm Zn and 90 ppm Si) or conventional Zn and Si fertilisers. These concentrations were selected following preliminary optimization trials with six different levels of Zn and Si nanoparticles, from which 10 ppm Zn and 90 ppm Si were identified as the most effective in supporting sugar beet growth without adverse effects. To evaluate salt stress resilience, plants were exposed to salinity stress levels of 0, 75, and 150 mM NaCl. To prevent osmotic shock, the target concentrations were achieved gradually by increasing NaCl at 25 mM per day. All treatments were conducted in a complete randomised design (CRD) with three replications per treatment, which is consistent with similar controlled-environment pot studies. The number of replicates was determined by the limited quantity of nanofertilizers and growth chamber space constraints.

2.3 | Measurements

2.3.1 | Agronomic and Physiological Measurements

Ion analysis samples were collected from the middle section of the fully expanded third leaf from the top after salt treatment, during the same growth stage for all plants, and in the morning to standardise the timing in sugar beet leaves. The third fully expanded leaf was selected because it is mature yet physiologically active and representative of ion accumulation. At harvest, key agronomic parameters were recorded, including shoot fresh weight (SFW), root fresh weight (RFW), shoot dry weight (SDW), root dry weight (RDW), root length (RL), and shoot length (SL). To assess leaf chlorophyll content before harvest, a chlorophyll meter (SPAD-502, Minolta Inc., Japan) was used, with readings taken at three points along the leaf blade from tip to base and averaged to ensure accuracy.

2.3.2 | Stomatal Conductance and Related Parameters

Transpiration rate (mmol H_2O $m^{-2}s^{-1}$), stomatal conductance (mol H_2O $m^{-2}s^{-1}$), intracellular CO_2 concentration (μmol CO_2 mol^{-1}), and photosynthetic rate (μmol CO_2 $m^{-2}s^{-1}$) were measured in sugar beet using a Li-COR 6400XT system (Li-COR Biosciences Inc.). To ensure reliability, each parameter was measured three times across different samples. Before taking measurements, the system was calibrated with a known CO_2 concentration. Fully expanded fifth leaves were chosen for the measurements, and a red LED light source (250 μmol photons $m^{-2}s^{-1}$) was used to maintain consistent illumination for photosynthetic evaluations.

2.3.3 | Osmotic Potential Measurement

To assess the osmotic potential in sugar beet shoots, leaves were cut and quickly frozen in liquid nitrogen. After a short freezing period, the leaves were thawed at room temperature and centrifuged at 327 g for 5 min using an Eppendorf 5810R centrifuge (GmbH, Germany) at 4°C to preserve the integrity of the cell sap. The resulting cell sap was then collected, and its osmotic potential was determined using a cryoscopic osmometer (Gonotec 030 GmbH, Germany).

2.3.4 | Extraction of Ions in Leaf Compartments

To examine ion movement and distribution, apoplastic washing fluid (AWF) was extracted from leaf tissues using an infiltration and centrifugation technique (Lohaus et al. 2001). The leaves were carefully trimmed, washed with deionised water, and then infiltrated with deionised water under a vacuum of 20 kPa to remove surface contaminants. Following infiltration, the leaves were centrifuged at 327***g*** for 5 min at 4°C, and the collected fluid was stored at −80°C for subsequent ion concentration analysis. After harvesting the AWF, the remaining leaf tissue was quickly frozen in liquid nitrogen, then centrifuged at 327***g*** for 10 min, and the resulting extract was kept at −80°C for ion quantification (Lohaus et al. 2001). The extract was analysed using ion chromatography with an anion exchange column to quantify key ions such as chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), phosphate (PO_4^{3-}), and organic acids. This method ensured accurate separation and quantification of ionic components in both the apoplastic and symplastic fractions of the leaf (Shahzad et al. 2013).

2.3.5 | Ionic and Silicon Analysis in Leaf Samples

To analyse sugar beet leaf samples, dried samples (200 mg) were digested using 10 mL of HNO_3 in a microwave oven. The resulting digest was diluted to 100 mL, and the concentrations of Zn, Na, and K were determined using inductively coupled plasma mass spectrometry (ICP-MS) to ensure high analytical

sensitivity (Wu et al. 2018). For silicon quantification, 100 mg of sugar beet leaf samples were processed using the oven-induced digestion (OID) method (Kraska and Breitenbeck 2010). The samples were treated with 30% hydrogen peroxide (H_2O_2) and heated at 95°C in a convection oven. After 30 min, the samples underwent alkali treatment with 50% NaOH, followed by the addition of 5 mM NH_4F to promote the formation of monosilicic acid (Kilmer 1965). The molybdenum blue method (Hallmark et al. 1983) was employed for colorimetric analysis at 650 nm using Ultraviolet–Visible Spectroscopy (UV-6000, R&M, UK), allowing for precise silicon quantification.

2.4 | Statistical Analysis

Data analysis was conducted using Statistix 10.1 software, with mean comparisons carried out using Least Significant Difference (LSD) at a 5% significance level (Steel et al. 1997). The results were presented as means ± standard error, with data visualisation done in Microsoft Excel. For advanced multivariate analyses, including heatmaps, Principal Component Analysis (PCA), and Pearson correlation matrices, R software version 4.4.2 was used.

3 | Results

3.1 | Agronomic Parameters

Nano and conv. Zn and Si significantly enhanced sugar beet agronomic performance under salinity stress ($p < 0.05$). Under non-saline conditions, shoot fresh weight increased by 39% and 46% with nano Zn and Si, respectively, with a similar trend at moderate 75 mM salinity. At high salinity level (150 mM), SFW increased 42% by nano Zn and 47% by nano Si compared to the control (Table 1). Root fresh weight declined with salinity but improved with nano treatments, increasing 7% by nano Zn and 10% by nano Si at 75 mM and showing similar improvement at 150 mM (Table 1). Shoot dry weight declined to 4.8 g at moderate salinity and 1.3 g at high salinity level but improved by 92% and 84% with nano Zn and nano Si at both levels (Table 1). Root dry weight showed substantial gains under 150 mM salinity, increasing by 54% and 67% with nano Zn and nano Si, respectively (Table 1). Nano treatments also boosted shoot length, with increases of 20%–29% under NS and 23%–35% at 75 mM salinity (Table 1). Root length was most affected at 150 mM, where nano Si enhanced it by 42% relative to the control (Table 1).

3.2 | Physiological Parameters

Physiological parameters of sugar beet were significantly influenced by salinity stress and nano and conv. treatments ($p < 0.05$). Nano Si increased the photosynthesis rate (A) by 95% at 75 mM and 104% at 150 mM, while nano Zn improved (A) by 98% and 133%, respectively (Table 2). Stomatal conductance (g_s) showed a significant increase with nano treatments, where nano Zn enhanced g_s by 2.5 times at 75 mM and 4.4 times at 150 mM, while nano Si improved it by 2.3 and 2.5 times, respectively, compared to the control (Table 2). Intracellular CO_2 concentration (C_i) decreased with salinity stress, where nano Zn/Si reduced C_i by 24% and 17% at 75 mM, and 21% and 24% at 150 mM, respectively (Table 2). Transpiration rate (E) improved with nano treatments, where nano Zn/Si increased E by 2.5% and 2.6% at 75 mM, and 2.9 and 3 times at 150 mM, respectively, compared to the control

TABLE 1 | Effect of different treatments (Nano Zn, Conv. Zn, Nano Si, and Conv. Si) on the agronomic performance of sugar beet under varying salinity stress (Control, 75 mM NaCl, 150 mM NaCl). Data represent mean values ± standard error (SE) for shoot fresh weight (SFW), shoot dry weight (SDW), root fresh weight (RFW), root dry weight (RDW), shoot length (SL), and root length (RL).

Stress	Treatments	SFW (g)	SDW (g)	RFW (g)	RDW (g)	SL (cm)	RL (cm)
Control	Control	20.4 ± 0.57	3.32 ± 0.17	6.50 ± 0.33	1.30 ± 0.05	31.0 ± 0.58	18.0 ± 0.58
	Nano Zn	28.4 ± 0.26	3.85 ± 0.05	7.50 ± 0.09	1.39 ± 0.12	37.3 ± 0.67	20.3 ± 0.33
	Conv. Zn	25.0 ± 0.30	3.41 ± 0.02	7.28 ± 0.09	1.33 ± 0.03	35.0 ± 0.00	18.7 ± 0.33
	Nano Si	29.9 ± 0.36	3.93 ± 0.01	9.80 ± 0.15	1.44 ± 0.12	40.0 ± 1.00	21.3 ± 0.33
	Conv. Si	27.8 ± 0.36	3.55 ± 0.03	7.89 ± 0.12	1.35 ± 0.03	34.5 ± 0.76	19.0 ± 0.58
75 mM NaCl	Control	37.1 ± 0.50	4.82 ± 0.17	9.90 ± 0.35	1.62 ± 0.07	27.0 ± 1.53	16.3 ± 0.33
	Nano Zn	42.3 ± 0.33	5.25 ± 0.05	10.6 ± 0.12	1.74 ± 0.05	33.3 ± 0.88	17.7 ± 0.33
	Conv. Zn	38.0 ± 0.82	5.15 ± 0.02	10.2 ± 0.06	1.64 ± 0.07	32.0 ± 0.58	16.7 ± 0.33
	Nano Si	43.5 ± 0.56	5.43 ± 0.01	10.9 ± 0.09	1.71 ± 0.05	36.7 ± 0.88	18.3 ± 0.33
	Conv. Si	38.5 ± 0.66	5.05 ± 0.03	10.0 ± 0.12	1.66 ± 0.07	34.7 ± 0.33	17.3 ± 0.33
150 mM NaCl	Control	13.0 ± 1.53	1.28 ± 0.06	5.80 ± 0.26	0.62 ± 0.04	11.3 ± 0.88	8.70 ± 0.33
	Nano Zn	18.5 ± 1.40	2.38 ± 0.09	6.70 ± 0.12	0.96 ± 0.08	20.0 ± 0.58	11.3 ± 0.33
	Conv. Zn	14.5 ± 1.51	1.30 ± 0.07	6.40 ± 0.06	0.92 ± 0.06	18.0 ± 0.00	10.3 ± 0.33
	Nano Si	19.2 ± 1.47	2.35 ± 0.09	7.30 ± 0.09	1.04 ± 0.07	23.0 ± 1.16	12.3 ± 0.33
	Conv. Si	15.5 ± 1.43	2.31 ± 0.05	6.60 ± 0.12	0.82 ± 0.01	16.8 ± 0.17	9.30 ± 0.33

TABLE 2 | Effects of conventional and nano fertilisers on photosynthetic rate (A), stomatal conductance (g_s), internal CO_2 concentration (C_i), transpiration rate (E), chlorophyll index (SPAD value), and (f) osmotic potential (ψ_s) in sugar beet under salt stress. The data represent mean values ± standard error (SE).

Stress	Treatments	A (μmol CO_2 $m^{-2}s^{-1}$)	g_s (mol H_2O $m^{-2}s^{-1}$)	C_i (μmol CO_2 mol^{-1})	E (mmol H_2O $m^{-2}s^{-1}$)	Ψ_s (mosmolkg^{-1})	SPAD
Control	Control	9.3 ± 0.18	0.07 ± 0.002	129 ± 3.79	1.12 ± 0.01	318 ± 4.41	39.67 ± 1.20
	Nano Zn	19.3 ± 0.24	0.20 ± 0.001	100 ± 2.89	2.81 ± 0.03	283 ± 8.83	41.67 ± 1.20
	Conv. Zn	16.6 ± 0.29	0.19 ± 0.003	109 ± 2.08	1.84 ± 0.02	313 ± 12.03	40.67 ± 1.20
	Nano Si	21.9 ± 0.32	0.23 ± 0.018	94 ± 2.34	2.85 ± 0.03	245 ± 5.01	42.67 ± 1.20
	Conv. Si	18.5 ± 0.12	0.18 ± 0.014	114 ± 3.06	2.38 ± 0.02	310 ± 5.01	40.00 ± 1.20
75 mM NaCl	Control	7.0 ± 0.12	0.06 ± 0.020	209 ± 1.45	0.64 ± 0.02	400 ± 2.89	41.67 ± 0.57
	Nano Zn	13.9 ± 0.07	0.15 ± 0.032	157 ± 2.91	1.61 ± 0.03	310 ± 2.89	48.00 ± 1.20
	Conv. Zn	11.9 ± 0.09	0.08 ± 0.008	179 ± 2.41	0.87 ± 0.34	340 ± 2.89	43.00 ± 1.52
	Nano Si	13.6 ± 0.31	0.13 ± 0.001	172 ± 6.02	1.65 ± 0.03	320 ± 2.89	48.33 ± 1.15
	Conv. Si	11.5 ± 0.18	0.10 ± 0.002	195 ± 2.61	1.18 ± 0.02	385 ± 2.89	43.33 ± 1.20
150 mM NaCl	Control	4.6 ± 0.35	0.03 ± 0.012	233 ± 8.83	0.46 ± 0.03	149 ± 3.06	32.33 ± 0.88
	Nano Zn	10.7 ± 0.33	0.13 ± 0.012	183 ± 7.70	1.33 ± 0.06	137 ± 4.41	35.00 ± 0.00
	Conv. Zn	8.2 ± 0.44	0.06 ± 0.009	193 ± 3.53	0.65 ± 0.29	145 ± 2.89	32.67 ± 0.66
	Nano Si	9.3 ± 0.33	0.08 ± 0.004	177 ± 4.41	1.38 ± 0.08	127 ± 1.45	36.33 ± 0.88
	Conv. Si	7.5 ± 0.29	0.08 ± 0.003	202 ± 4.41	1.04 ± 0.03	148 ± 2.08	33.67 ± 0.33

(Table 2). Chlorophyll content (SPAD) declined with increasing salinity, but nano Si improved SPAD by 16% at 75 mM and 9% at 150 mM compared to the control, while nano Zn had a slightly lower effect (Table 2). Osmotic potential (ψ_s) became more negative with salinity, with nano Zn/Si reducing the percentage decline at 75 mM. At 150 mM, nano Zn/Si mitigated the decline by 8% and 14%, respectively (Table 2).

3.3 | Chemical Parameters

3.3.1 | Mitigation of Sodium Accumulation by Zn and Si

Salinity stress significantly increased Na^+ accumulation in both shoots and roots, peaking at the highest salinity level (150 mM NaCl). However, nano Zn and nano Si significantly reduced Na^+ uptake, with nano Zn showing the most pronounced reduction in shoots (Table 3) and nano Si being more effective in roots at 150 mM NaCl (Table 3). For K^+, nano Si consistently showed the greatest enhancement, with a 20% increase in shoots even under control conditions and a 40% increase under moderate salinity level (75 mM NaCl) (Table 3). In roots, nano Si also led to the highest K^+ accumulation, increasing by 14% at 150 mM (Table 3). Zn accumulation was significantly influenced by nano Zn and nano Si. At 75 mM NaCl, nano Zn had the highest Zn content in shoots (1.47 mg/kg DW), while at 150 mM, both nano Zn and nano Si maintained the highest levels of Zn (1.2 mg/kg DW) (Table 3). In terms of Si accumulation, nano Si showed the highest content at both salinity levels, with 1.42 mg/g DW at 75 mM and 1.24 mg/g DW at 150 mM (Table 3).

3.3.2 | Ion Partitioning in Apoplast and Symplast

Nano and conv. Zn and Si significantly mitigated the effects of salinity stress. Nano Zn significantly reduced Na^+ content in the apoplast under both salinity levels, with a 48% decrease at 75 mM and 47% at 150 mM compared to the control (Figure 1a). In the symplast, nano Zn showed even greater efficacy, lowering Na^+ concentration by approximately 45% at 75 mM and 50% at 150 mM relative to the control (Figure 1b). Similarly, nano Si also substantially decreased Na^+ levels in both compartments under salinity stress, demonstrating enhanced sodium compartmentalization and improved salt tolerance (Figure 1a,b). Nano Si consistently enhanced potassium concentrations in both apoplast and symplast compartments, especially under salinity stress, indicating improved potassium retention. Nano Zn also improved K^+ levels but to a slightly lesser extent (Figure 1c,d).

In the apoplast, nano Zn reduced Cl^- content by 16% and nano Si by 21% compared to the control under 75 mM salinity. At 150 mM, nano Si significantly decreased Cl^- content by 24% relative to the control (Figure 1e). In the symplast, nano Si and nano Zn reduced chloride content by 27% and 19%, respectively, under 75 mM salinity. At 150 mM, the reduction remained 27% with nano Si and 19% with nano Zn (Figure 1f). Nano Zn enhanced NO_3^- content by 1.74 times and nano Si by 1.86 times at 75 mM, while at 150 mM, nano Zn increased it by 1.74 times and nano Si by 1.83 times compared to the control (Figure 1g). A similar trend was observed in the symplast, where both nano Zn/Si increased NO_3^- content by the same magnitude as in the apoplast under 75 mM. However, at 150 mM, both treatments

TABLE 3 | Effect of conventional and Nano fertilisers on nutrient accumulation in shoots and roots of sugar beet under different salinity levels. Data represents mean values ± standard error (SE).

Stress	Treatments	Na^+ in shoot ($mg\,g^{-1}$ DW)	Na^+ in root ($mg\,g^{-1}$ DW)	K^+ in shoot ($mg\,g^{-1}$ DW)	K^+ in root ($mg\,g^{-1}$ DW)	Si^{4+} in shoot ($mg\,g^{-1}$ DW)	Zn^{2+} in shoot ($mg\,kg^{-1}$ DW)
Control	Control	5.60 ± 0.20	4.60 ± 0.21	27.3 ± 0.25	21.6 ± 0.30	0.27 ± 0.04	0.05 ± 0.01
	Nano Zn	4.83 ± 0.16	3.83 ± 0.17	35.0 ± 0.58	23.8 ± 0.39	0.31 ± 0.04	3.08 ± 0.30
	Conv. Zn	5.20 ± 0.17	4.20 ± 0.17	31.0 ± 1.53	22.0 ± 0.15	0.28 ± 0.04	2.67 ± 0.34
	Nano Si	4.20 ± 0.15	3.20 ± 0.15	38.2 ± 0.73	24.5 ± 0.29	1.53 ± 0.09	0.10 ± 0.03
	Conv. Si	4.90 ± 0.21	3.90 ± 0.21	35.7 ± 0.33	22.5 ± 0.26	1.33 ± 0.12	0.07 ± 0.02
75 mM NaCl	Control	24.67 ± 3.39	26.0 ± 0.58	23.8 ± 1.59	15.3 ± 0.78	0.17 ± 0.02	0.03 ± 0.01
	Nano Zn	14.0 ± 1.16	11.0 ± 1.20	26.7 ± 1.45	16.9 ± 0.52	0.23 ± 0.02	1.47 ± 0.15
	Conv. Zn	20.7 ± 0.88	13.67 ± 0.88	24.0 ± 0.58	15.8 ± 0.70	0.20 ± 0.02	1.20 ± 0.12
	Nano Si	18.0 ± 1.53	13.67 ± 3.18	28.7 ± 0.88	17.5 ± 0.29	1.42 ± 0.04	1.38 ± 0.09
	Conv. Si	20.0 ± 1.16	16.0 ± 1.16	26.5 ± 0.74	15.5 ± 0.25	1.21 ± 0.03	1.17 ± 0.12
150 mM NaCl	Control	38.33 ± 2.03	41.0 ± 0.58	15.8 ± 0.61	7.6 ± 0.32	0.23 ± 0.09	0.00 ± 0.00
	Nano Zn	19.67 ± 0.88	19.67 ± 0.88	20.2 ± 0.60	10.5 ± 0.29	0.30 ± 0.10	1.20 ± 0.06
	Conv. Zn	21.33 ± 0.88	23.0 ± 1.53	16.0 ± 0.87	8.5 ± 0.26	0.30 ± 0.13	1.00 ± 0.06
	Nano Si	19.0 ± 0.58	18.0 ± 1.16	22.2 ± 0.44	11.2 ± 0.27	1.24 ± 0.03	1.20 ± 0.10
	Conv. Si	21.67 ± 1.20	19.3 ± 0.88	17.9 ± 1.57	7.8 ± 0.44	1.07 ± 0.07	0.99 ± 0.13

resulted in a twofold increase in NO_3^- content compared to the control (Figure 1h).

3.3.3 | Determination of Apoplastic and Symplastic Organic Acids

Organic acid accumulation was influenced by salinity stress, with nano Zn and Si showing significant effects in most cases. In the apoplast, nano Zn significantly increased malic acid content under both 75 and 150 mM salinity conditions, followed by nano Si and conv. treatments (Figure 2a). In the symplast, both nano Zn and Si increased malic acid levels by approximately 1-fold compared to the control (Figure 2b). A similar trend was observed for citric acid in both apoplast and symplast (Figure 2c,d). For oxalate, nano Zn reduced its content by 22% and 24% at 75 and 150 mM, respectively, in the apoplast (Figure 2e). However, in the symplast, no significant changes were observed under either salinity condition, and there was no notable difference between the nano and conv. fertilizers (Figure 2f).

3.3.4 | Determination of Apoplastic and Symplastic Sugar Contents

Nano and conv. forms of Zn and Si significantly influenced sugar content under salinity stress. In the apoplast, glucose content increased by 61% with nano Zn and Si at 75 mM salinity (Figure 3a). At 150 mM, nano Zn increased glucose by 53%, while nano Si increased it by 45% compared to the control (Figure 3a). In the symplast, nano Zn led to a glucose concentration of 37 mg/L, while nano Si resulted in 26 mg/L at 75 mM. At 150 mM, glucose content was 14 mg/L with nano Zn and 17 mg/L with nano Si (Figure 3b). For fructose, nano Zn increased content by 56%, and nano Si by 25% at 75 mM salinity in the apoplast. At 150 mM, the increase was 49% and 21% for nano Zn/Si, respectively (Figure 3c). In the symplast, fructose followed a similar trend as glucose (Figure 3d). Regarding sucrose, nano Zn increased content by 39%, and nano Si by 36% at 75 mM salinity in the apoplast. At 150 mM, sucrose content increased by 43% with nano Zn and 28% with nano Si (Figure 3e). A similar trend was observed in symplast sucrose levels (Figure 3f).

3.4 | Heatmap Analysis

The correlation heatmap of combined apoplastic (Apo) and symplastic (Symp) data shows significant compartmentalization of key ions and metabolites under salinity stress. Na^+ content in shoots (Na cont) and Cl^- exhibit strong correlations within apoplast and symplast compartments. Organic acids such as oxalate, malic acid, and citric acid, along with sugars including sucrose, glucose, and fructose, display coordinated variations, indicating that nano Zn and nano Si influence their compartmental distribution, enhancing ion sequestration and metabolic regulation (Figure 4).

The heatmap of agronomic, chemical, and physiological parameters illustrates strong positive correlations among intracellular CO_2 concentration, osmotic potential, root dry weight, shoot fresh weight, chlorophyll content, transpiration rate, photosynthetic rate, and stomatal conductance. This confirms that nano

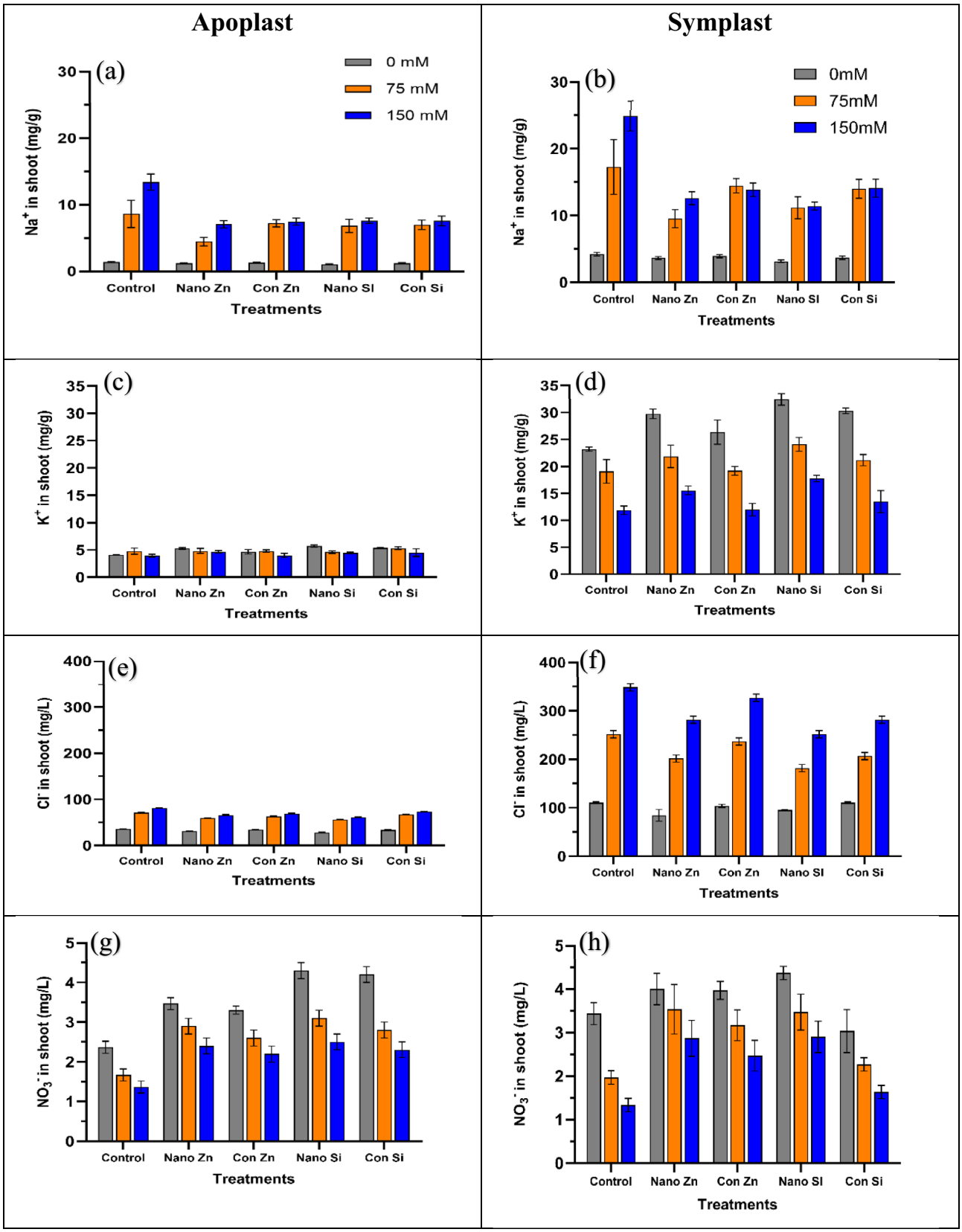


FIGURE 1 | Effects of different silicon and zinc sources on ionic profiles in sugar beet under saline and non-saline conditions. Analysed variables: (a) Na^+ content in the apoplast, (b) Na^+ content in the symplast, (c) K^+ content in the apoplast, (d) K^+ content in the symplast, (e) Cl^- content in the apoplast, (f) Cl^- content in the symplast, (g) NO_3^- content in the apoplast, and (h) NO_3^- content in the symplast. Error bars correspond to standard error (SE).

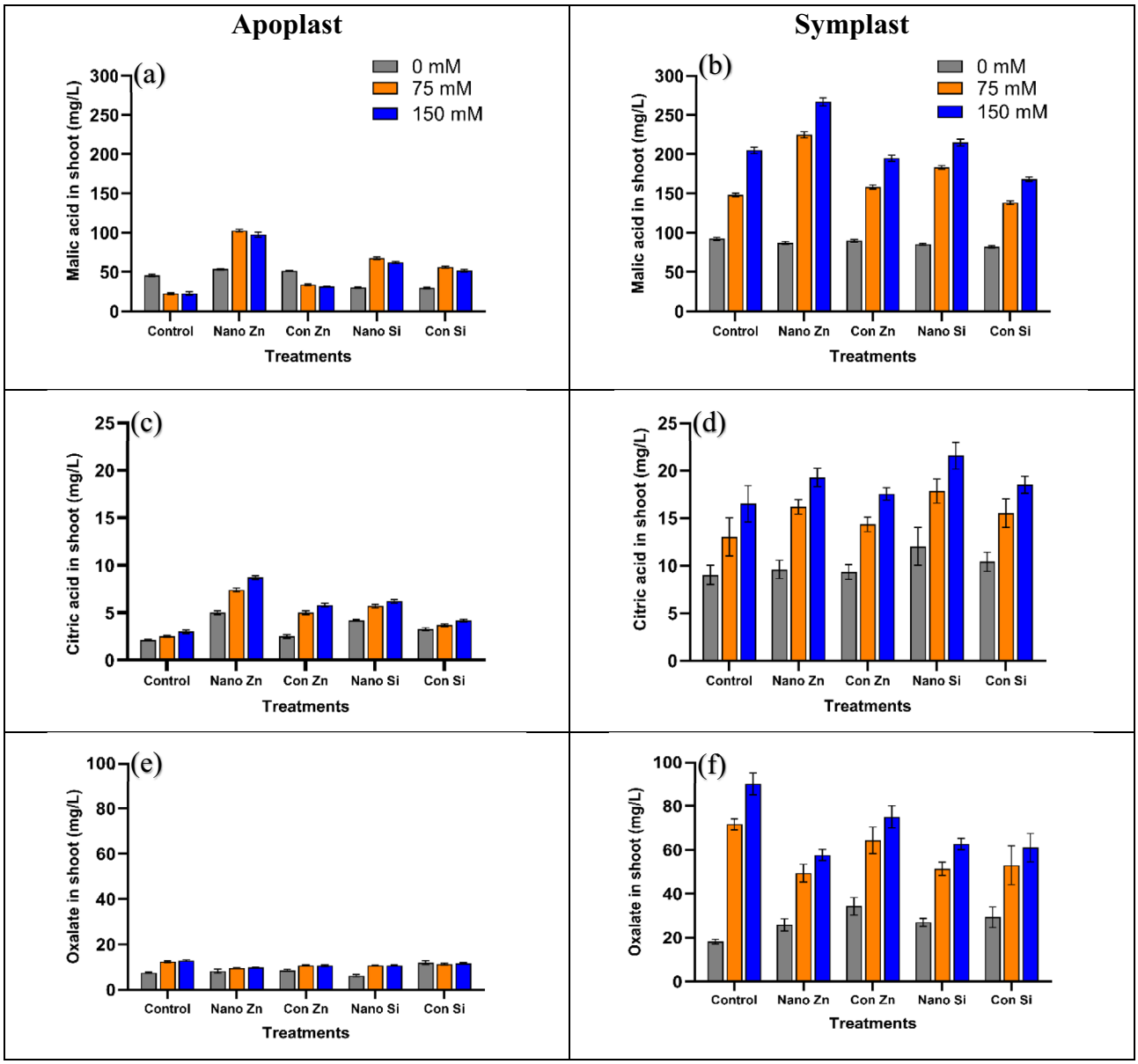


FIGURE 2 | Effects of silicon and zinc sources on organic acid profiles in sugar beet under saline and non-saline conditions. The figure presents: (a) Malic acid in apoplast, (b) Malic acid in symplast, (c) Citric acid in apoplast, (d) Citric acid in symplast, (e) Oxalate in apoplast, and (f) Oxalate in symplast. Error bars represent the standard error (SE).

Zn and nano Si positively affect nutrient uptake and overall physiological performance under salinity stress (Figure 4).

3.5 | Principal Component Analysis (PCA)

The PCA analysis of apoplastic and symplastic data revealed distinct patterns reflecting the effects of salinity stress (75 mM and 150 mM NaCl) and treatments with nano Zn, nano Si, conv. zinc, and conv. Si. In the apoplastic and symplastic, the first two components capture a substantial portion of the data variance and distinctly separate nano-fertiliser from controls and conventional applications. Nano Zn and nano Si are closely associated with enhanced compartmentalization of Na^+ and Cl^-, alongside increased accumulation of key osmolytes such as glucose, fructose, sucrose, malic acid, citric acid, and oxalate in both apoplast and symplast (Figure 5).

Conversely, the PCA of agronomic, chemical, and physiological traits demonstrates that nano Zn and nano Si under both salinity levels cluster separately from the control and conventional treatments, showing enhanced photosynthetic capacity, stomatal conductance, transpiration rate, intracellular CO_2, chlorophyll content, and biomass indicators such as root dry weight and shoot fresh weight. Control and conventional treatments under high salinity exhibit close clustering, indicating impaired physiological function and growth (Figure 5).

3.6 | Pearson Correlation Analysis

The Pearson correlation analysis revealed significant linear relationships among key variables under salinity stress. Strong positive correlations were observed between essential growth parameters (e.g., shoot fresh weight, root dry weight)

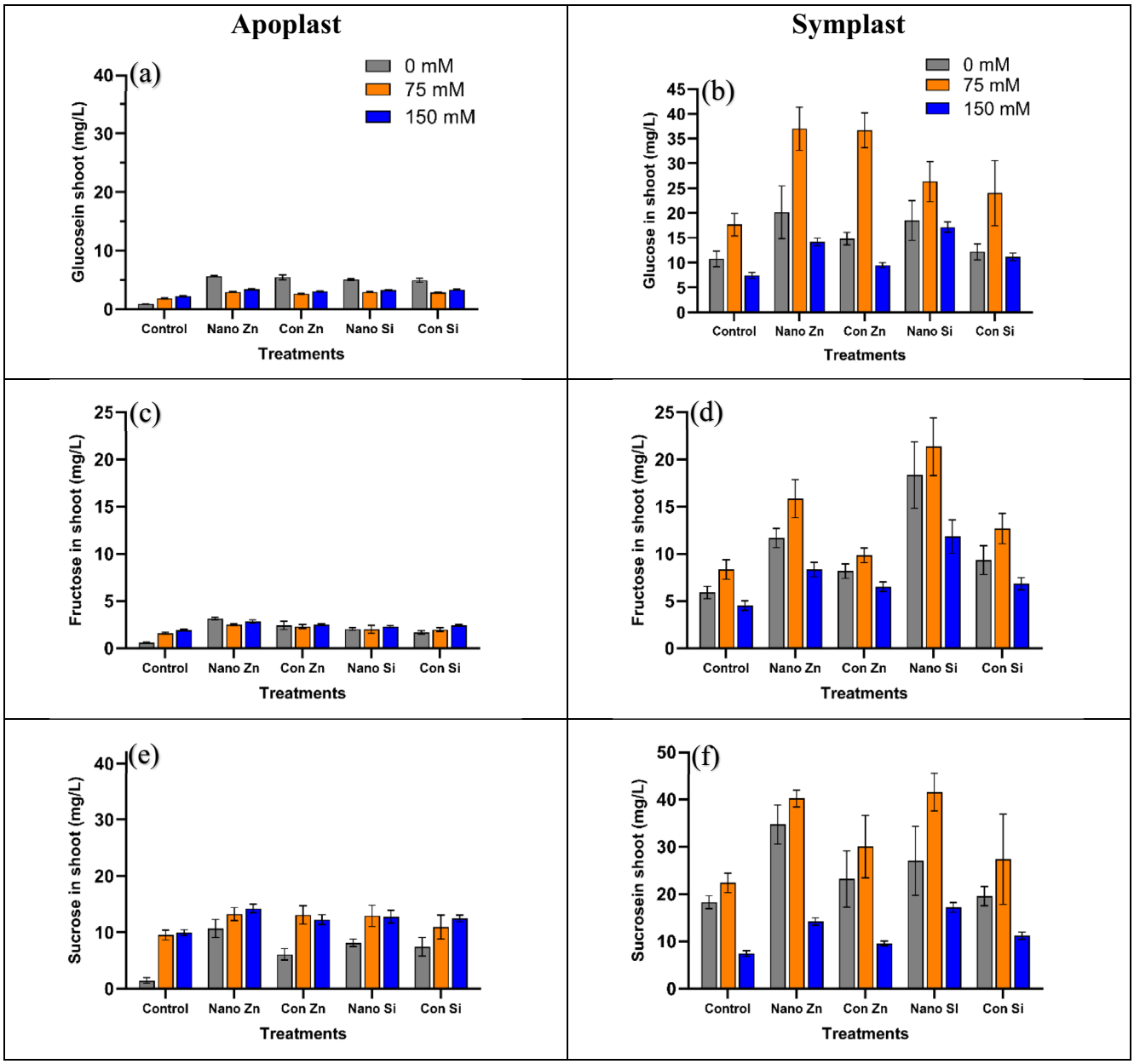


FIGURE 3 | Effects of different silicon and zinc sources on sugar profiles in sugar beet under saline and non-saline conditions. (a) Glucose levels in the apoplast, (b) Glucose levels in the symplast, (c) Fructose levels in the apoplast, (d) Fructose levels in the symplast, (e) Sucrose levels in the apoplast, and (f) Sucrose levels in the symplast. Error bars represent standard error (SE).

and photosynthetic traits (e.g., chlorophyll content, photosynthetic rate), indicating coordinated physiological responses. Additionally, negative correlations between osmotic potential and growth-related traits confirmed the adverse effects of salinity-induced osmotic stress. Ion contents such as Na^+ and Cl^- showed inverse relationships with K^+ and organic metabolites, highlighting the importance of ion homeostasis (Figure 6a). Specifically, in the apoplastic and symplastic compartments, sodium and chloride exhibited strong negative correlations with potassium and key organic acids (malic acid, citric acid, oxalate) and sugars (sucrose, glucose, fructose). This pattern suggests effective ion compartmentalization and enhanced metabolic regulation mediated by nano zinc and silicon. Positive correlations among organic acids and sugars further indicate their role in osmotic adjustment and stress mitigation (Figure 6b).

4 | Discussion

4.1 | Physiological and Growth Improvements With Nano Fertilisation Under Salinity Stress

Salinity stress is a major abiotic factor that adversely affects plant growth, metabolism, and productivity by disrupting ion homeostasis, water uptake, and essential physiological functions (Singh et al. 2024; Alavilli et al. 2023). To mitigate these negative effects, nanofertilizers could be helpful due to their higher bioavailability, controlled nutrient release, and enhanced efficiency to reach subcellular compartments compared to their conventional counterparts (Shoukat, Saqib, et al. 2024; Shabiya et al. 2025). In the present study, we investigated how nanofertilizers help plants in their ion regulation, sugar accumulation, and organic acid content compared to conventional fertilizers

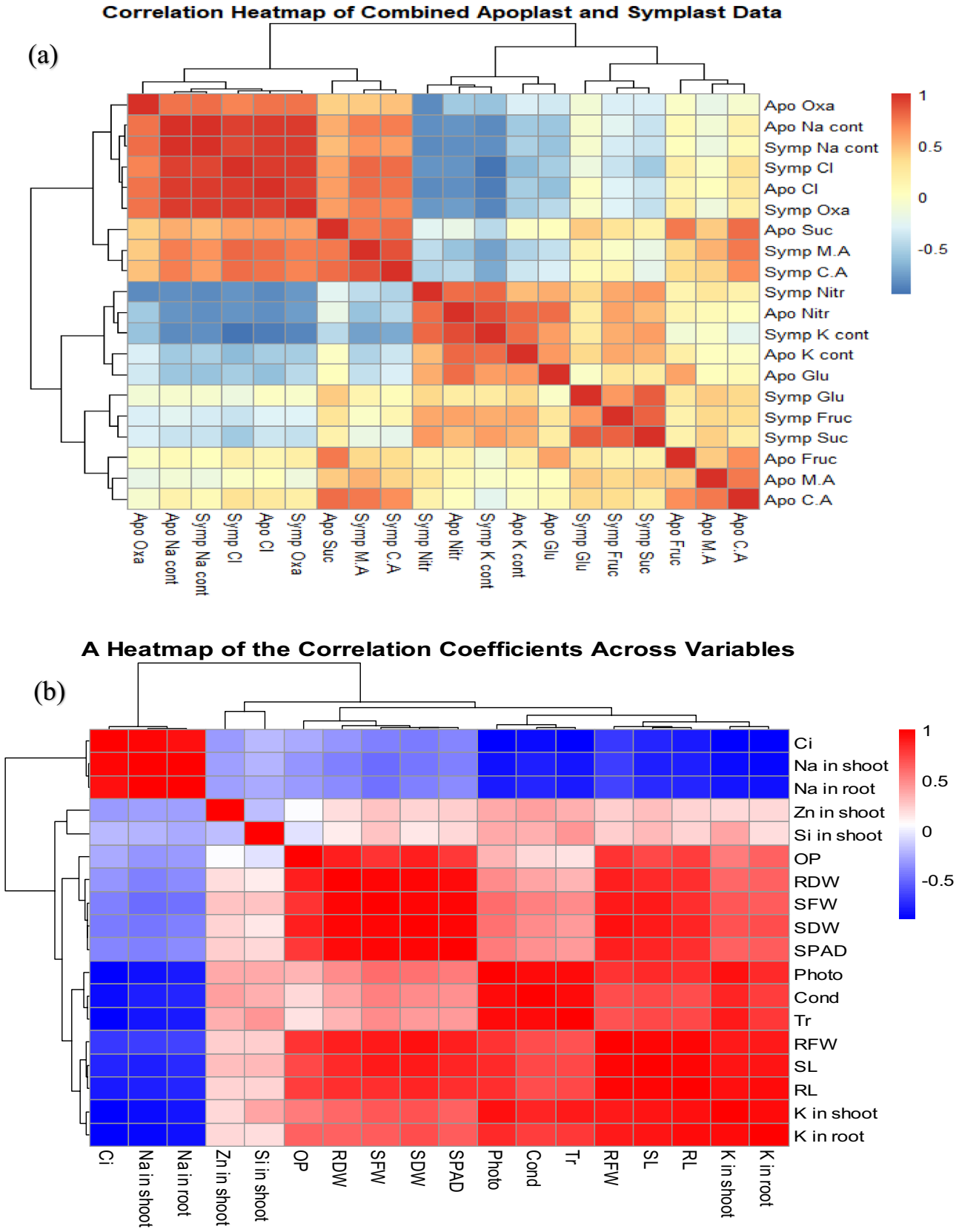


FIGURE 4 | Legend on next page.

on sugar beet (*Beta vulgaris* L.) grown under saline conditions. Among the key findings, nano Si led to a 30% reduction in shoot and root Na^+, while nano Zn significantly increased shoot K^+ content by 28% and enhanced the K^+/Na^+ ratio by 2.6-fold, indicating a critical synergistic effect on K^+ retention (Table 3). These changes were accompanied by elevated sugar accumulation and

FIGURE 4 | Correlation heatmaps of (a) apoplastic-symplastic ion and (b) agronomic, chemical, and physiological parameters. The upper figure shows correlations in apoplastic (Apo) and symplastic (Symp) compartments for ions and metabolites including sodium content (Na cont), chloride (Cl), oxalate (Oxa), nitrate (Nitr), potassium content (K cont), sucrose (Suc), glucose (Glu), fructose (Fruc), malic acid (M.A.), and citric acid (C.A.). The lower figure depicts correlations among agronomic and physiological parameters including intracellular CO_2 concentration (C_i), osmotic potential (Op), root dry weight (RDW), shoot fresh weight (SFW), chlorophyll content (SPAD), transpiration rate (Tr), photosynthetic rate (Photo), and stomatal conductance (Conduc).

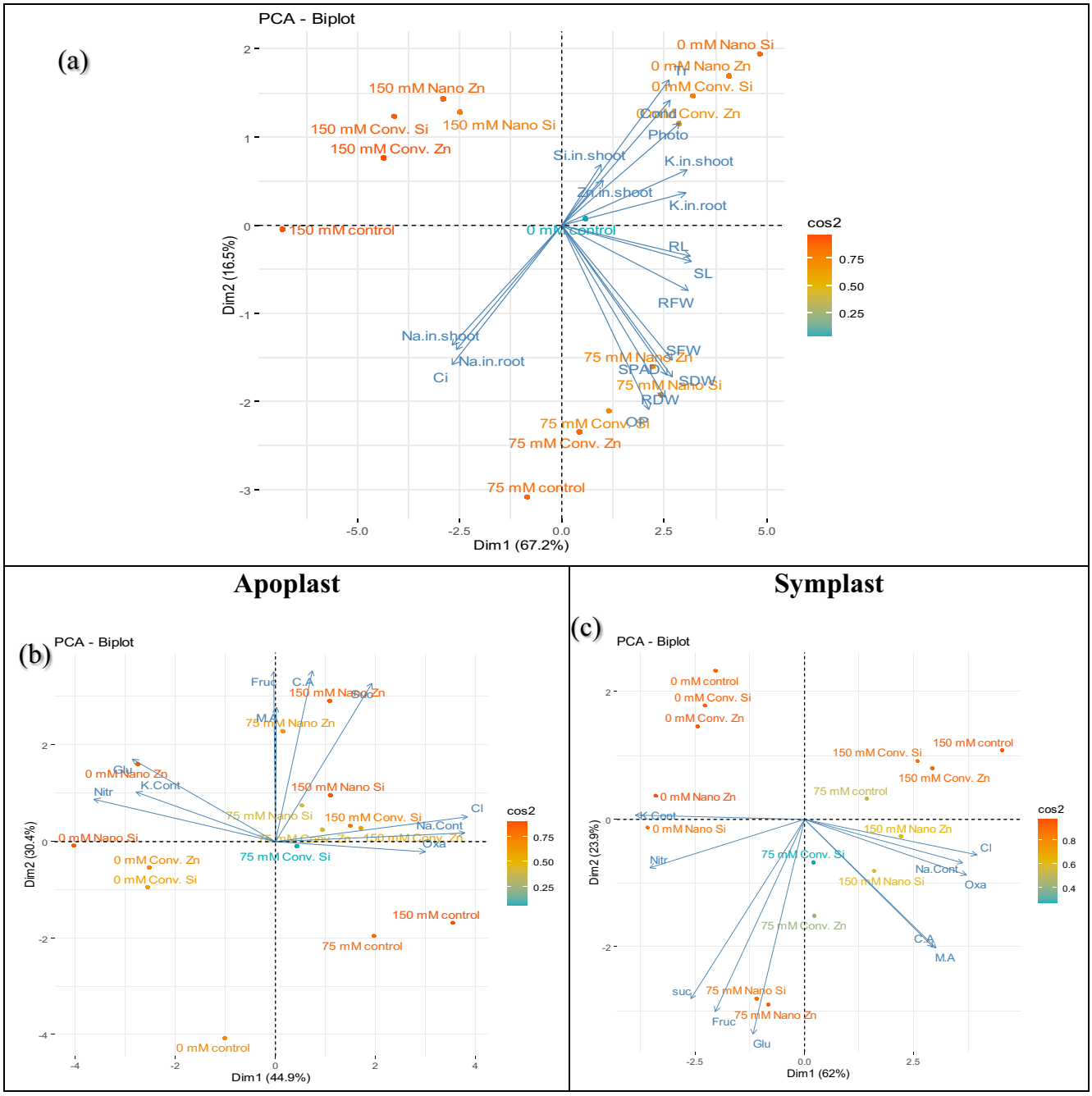


FIGURE 5 | PCA biplots illustrating the effects of nano and conventional zinc (Zn) and silicon (Si) treatments on sugar beet under non-saline (0 mM) and saline (75 mM and 150 mM NaCl) conditions. Panels show: (a) ion homeostasis, photosynthetic parameters, and growth traits, (b) apoplastic (Apo) compartment, and (c) symplastic (Symp) compartment. Variables include intracellular CO_2 concentration (C_i), osmotic potential (Op), root dry weight (RDW), shoot fresh weight (SFW), chlorophyll content (SPAD), transpiration rate (Tr), photosynthetic rate (Photo), and stomatal conductance (Conduc). Ion and metabolite measurements in the apoplast and symplast encompass sodium content (Na cont), chloride (Cl), oxalate (Oxa), nitrate (Nitr), potassium content (K cont), sucrose (Suc), glucose (Glu), fructose (Fruc), malic acid (M.A.), and citric acid (C.A.). Treatments include nano zinc (Nano Zn), nano silicon (Nano Si), conventional zinc (Conv. Zn), and conventional silicon (Conv. Si).

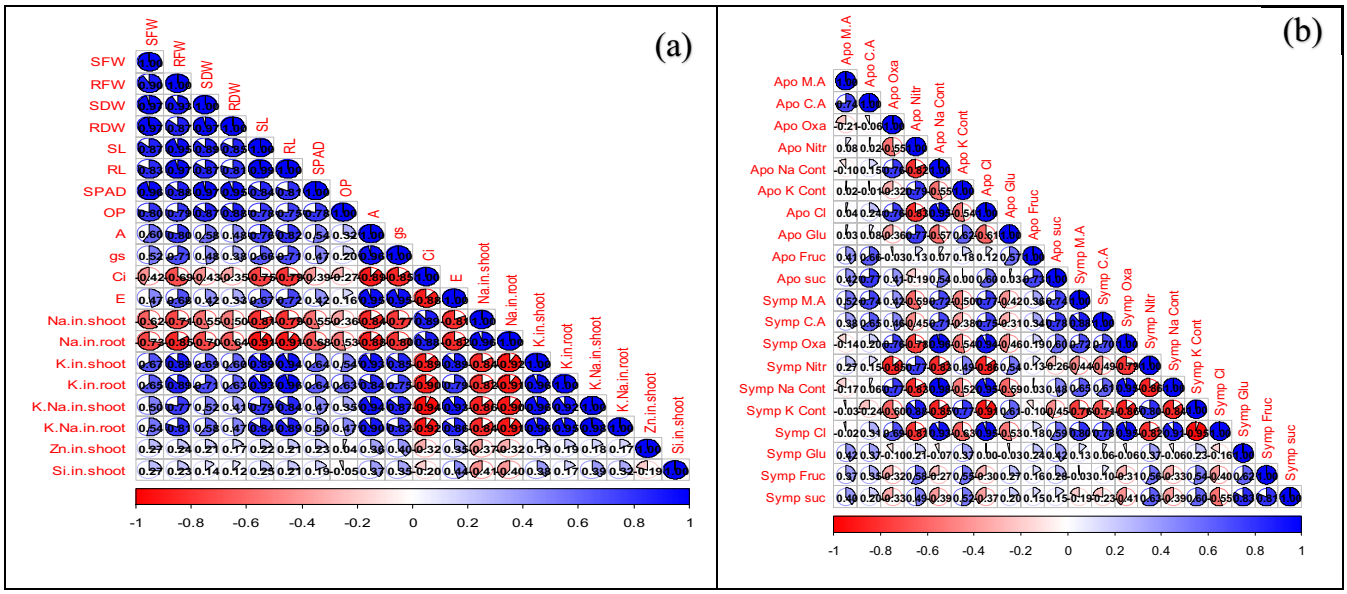


FIGURE 6 | Pearson correlation matrix of (a) agronomic, physiological, and chemical parameters, (b) apoplastic and symplastic metabolites and ions in sugar beet under salinity stress. Figure (a) presents correlations among growth traits (shoot fresh weight [SFW], root dry weight [RDW]), physiological traits (chlorophyll content [SPAD], photosynthetic rate [Photo], stomatal conductance [Conduc], transpiration rate [Tr], intracellular CO_2 concentration [C_i], osmotic potential [Op]), and chemical parameters. Figure (b) illustrates correlations among ions (Na content, Cl, K content), organic acids (malic acid [M.A.], citric acid [C.A.], oxalate [Oxa]), nitrates (Nitr), and sugars (sucrose [Suc], glucose [Glu], fructose [Fruc]) in apoplastic (Apo) and symplastic (Symp) compartments.

organic acid adjustments, particularly increased malic and citric acid levels, which played central roles in osmotic adjustment (Moradinezhad and Ranjbar 2024). Furthermore, nano Zn and nano Si significantly enhanced photosynthetic parameters, including net photosynthetic rate, stomatal conductance, and chlorophyll content (Table 2). Nano Zn outperformed nano Si in enhancing the net photosynthetic rate, with a 98% increase at 75 mM and 133% at 150 mM, while nano Si showed 95% and 104% increases, respectively. Nano Zn also had a stronger effect on stomatal conductance, enhancing it by 2.5 times at 75 mM and 4.4 times at 150 mM, compared to nano Si's 2.3 and 2.5 times improvement, respectively (Table 2). These improvements reflect reduced ionic and oxidative damage due to effective ion sequestration and antioxidant defense activation promoted by nanonutrients (Faizan et al. 2024). Enhanced stomatal conductance optimizes CO_2 assimilation, while chlorophyll stabilization maintains light-harvesting efficiency, thus supporting higher biomass accumulation under salinity stress (Zhang et al. 2020). The enhanced salt tolerance provided by nano Zn and nano Si is due to their combined ability to regulate ion transporters, facilitating effective Na^+ and Cl^- compartmentalization, preserving K^+ homeostasis, and inducing metabolic changes through organic acids and sugars that help maintain osmotic balance and bolster antioxidative defenses (Almutairi 2016; Hassan et al. 2023). These well-coordinated physiological and biochemical processes ensure the continued growth and productivity of sugar beet under stressful saline conditions.

4.2 | Ion Compartmentalization Under Salinity Stress

Salinity stress mainly hampers plant growth through ionic toxicity resulting from the excessive accumulation of Na^+ and Cl^-, which disrupts cellular metabolism and osmotic balance (Jajoo 2012). Our findings demonstrate that nano Zn and nano Si effectively alleviate this toxicity by promoting the sequestration and compartmentalization of these ions within sugar beet tissues. The marked reductions in Na^+ and Cl^- levels in both the apoplastic and symplastic compartments under nano treatments suggest their role in regulating ion distribution, thereby reducing the cytoplasmic exposure to harmful ions (Figure 1a–f). These findings imply that nano Zn and nano Si may penetrate subcellular spaces more efficiently than their conventional counterparts (Shoukat, Pitann, Zafar, et al. 2024). This enhanced localization potentially supports better ion compartmentalization, alleviating ionic toxicity under salinity stress (Zhang et al. 2024; Qian et al. 2024).

Notably, nano Si exhibited a slightly superior ability to reduce symplastic Na^+ and Cl^-, emphasizing its role in promoting vacuolar sequestration and selective ion inclusion. This could be attributed to silicon's impact on its deposition in apoplastic barriers, which restrict ion influx and enhance compartmentalization (Upadhyaya and Roychoudhury 2024). Additionally, the improved retention of K^+ observed with nano treatments (Figure 1c,d) is crucial for maintaining the K^+/Na^+ ratio, which is vital for enzyme activation, osmotic regulation, and photosynthetic efficiency under salt stress (Adem et al. 2014). The effective balance between Na^+ exclusion from the cytosol and K^+ retention, facilitated by nanonutrients, contributes to the enhanced physiological performance observed.

4.3 | Metabolic Adjustments: Organic Acids and Sugars in Osmotic Regulation

Alongside ion homeostasis, nano Zn and nano Si increased organic acids such as malate and citrate in both apoplast and

symplast (Figure 2a–d). These organic acids serve as osmolytes that adjust cellular osmotic potential and stabilize enzyme structures, thus protecting metabolic pathways during ionic stress. The accumulation of organic acids, such as malate and citrate, plays a crucial role in interacting with ion sequestration mechanisms, particularly in the compartmentalization of toxic ions like Na^+ and Cl^- into vacuoles. This compartmentalization is an essential mechanism for mitigating the harmful effects of these ions in the cytoplasm, as it isolates them in vacuoles, where their concentration is less harmful to cellular function (Flowers et al. 2015; Shoukat, Pitann, Zafar, et al. 2024). The organic acids themselves act as counterions, helping to maintain osmotic balance within the vacuoles while enabling the sequestration of Na^+ and Cl^-. This synergy between organic acid accumulation and ion compartmentalization enhances the plant's overall salt tolerance by reducing the toxic impact of Na^+ and Cl^- in the cytoplasm, thus promoting better cell function under saline conditions (Bendaly et al. 2016; Rakesh et al. 2024). The concurrent accumulation of sugars (glucose, fructose, sucrose) in apoplastic and symplastic compartments (Figure 3a–f) further reinforces osmotic adjustment and provides metabolic energy, contributing to overall stress resilience (Tuteja 2007).

Heatmap, PCA, and correlation analyses confirm that nano Zn and nano Si enhance coordinated ion compartmentalization and metabolic adjustments under salinity (Figures 4–6). Key toxic ions (Na^+, Cl^-) negatively correlate with potassium, organic acids, and sugars, indicating improved ionic homeostasis and osmotic adjustment. Nanoparticle treatments cluster distinctly from controls, associating with increased osmolytes, photosynthetic efficiency, and biomass, highlighting their role in sustaining growth and physiological function under salt stress (Figures 4–6).

5 | Conclusions

This study demonstrates that nano Zn/Si fertilisation significantly enhances K^+ homeostasis, osmotic adjustment, and overall plant resilience in sugar beet under salinity stress. Nano Zn primarily contributes to improved photosynthetic efficiency, stomatal conductance, and K^+ retention, leading to a 28% increase in shoot K^+ content and a 2.6-fold enhancement in the K^+/Na^+ ratio, which directly contributes to better biomass production. In contrast, nano Si plays a crucial role in Na^+ exclusion, reducing Na^+ content in shoots by 30% and in roots by 40%, while also improving structural reinforcement and enhancing water uptake. Additionally, both nano Zn and nano Si improved organic acid accumulation, with nano Zn increasing malic acid content by 35% at 75 mM NaCl, facilitating osmotic adjustment and stress detoxification mechanisms. The combined effects of nano Zn/Si contribute to a synergistic improvement in salt resistance, promoting better growth, nutrient uptake, and stress adaptation in sugar beet. These findings highlight the potential of nano-fertilisers as an efficient and sustainable strategy for improving crop resilience in saline environments. Future research should explore the long-term effects of nano Zn/Si fertilisation on plant health, soil interactions, and environmental safety to optimise their agricultural applications.

Author Contributions

Conceptualization, A.S. K.H.M. and Z.A.S., Methodology and Formal Analysis, A.S. B.P. and Md.S.H., Writing – Original Draft Preparation, A.S. Writing – Review and Editing, B.P. A.N. H.A. and K.H.M., Supervision, K.H.M. and Z.A.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

References

Adem, G. D., S. J. Roy, M. Zhou, J. P. Bowman, and S. Shabala. 2014. "Evaluating the Contribution of Ionic, Osmotic, and Oxidative Stress Components Towards Salinity Tolerance in Barley." *BMC Plant Biology* 14: 1–13. https://doi.org/10.1186/1471-2229-14-113.

Adler, G., E. Blumwald, and D. Bar-Zvi. 2010. "The Sugar Beet Gene Encoding the Sodium/Proton Exchanger 1 (BvNHX1) is Regulated by a MYB Transcription Factor." *Planta* 232: 187–195. https://doi.org/10.1007/s00425-010-1160-7.

Alavilli, H., S. Yolcu, M. Skorupa, S. B. Aciksoz, and M. Asif. 2023. "Salt and Drought Stress-Mitigating Approaches in Sugar Beet (*Beta vulgaris* L.) to Improve Its Performance and Yield." *Planta* 258: 30. https://doi.org/10.1007/s00425-023-04189-x.

Alharbi, K., E. Hafez, A. E. D. Omara, A. Awadalla, and Y. Nehela. 2022. "Plant Growth Promoting Rhizobacteria and Silica Nanoparticles Stimulate Sugar Beet Resilience to Irrigation with Saline Water in Salt-Affected Soils." *Plants* 11, no. 22: 3117.

Almutairi, Z. M. 2016. "Effect of Nano-Silicon Application on the Expression of Salt Tolerance Genes in Germinating Tomato (*Solanum lycopersicum* L.) Seedlings Under Salt Stress." *Plant Omics* 9, no. 1: 106–114.

Arif, Y., P. Singh, H. Siddiqui, A. Bajguz, and S. Hayat. 2020. "Salinity Induced Physiological and Biochemical Changes in Plants: An Omic Approach Towards Salt Stress Tolerance." *Plant Physiology and Biochemistry* 156: 64–77. https://doi.org/10.1016/j.plaphy.2020.08.042.

Azlina, H., J. Hasnidawani, H. Norita, and S. Surip. 2016. "Synthesis of SiO_2 Nanostructures Using Sol-Gel Method." *Acta Physica Polonica* 129: 842–844. https://doi.org/10.1016/j.proche.2016.03.095.

Bendaly, A., D. Messedi, A. Smaoui, R. Ksouri, A. Bouchereau, and C. Abdelly. 2016. "Physiological and Leaf Metabolome Changes in the Xerohalophyte Species *Atriplex halimus* Induced by Salinity." *Plant Physiology and Biochemistry* 103: 208–218. https://doi.org/10.1016/j.plaphy.2016.02.037.

Chen, C., J. Liu, P. Liu, and B. Yu. 2011. "Investigation of Photocatalytic Degradation of Methyl Orange by Using Nano-Sized ZnO Catalysts." *Advances in Chemical Engineering and Science* 1: 9–14. https://doi.org/10.4236/aces.2011.11002.

Chhabra, R. 2022. "Management and reclamation of saline soils." In *Salt-Affected Soils and Marginal Waters: Global Perspectives and Sustainable Management*, 101–160. Springer International Publishing. https://doi.org/10.1007/978-3-030-78435-5_3.

Faizan, M., P. Alam, A. Hussain, et al. 2024. "Phytochelatins: Key Regulator Against Heavy Metal Toxicity in Plants." *Plant Stress* 11: 100355. https://doi.org/10.1016/j.stress.2024.100355.

FAO. 2024a. *FAO Launches First Major Global Assessment of Salt-Affected Soils in 50 Years*. Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/newsroom/detail/fao-launches-first-major-global-assessment-of-salt-affected-soils-in-50-years/en.

FAO. 2024b. "Global Food Production at Increased Risk From Excess Salt in Soil, UN Report Warns." *The Guardian*. https://www.theguardian.com/environment/2024/dec/11/global-food-production-at-increased-risk-from-excess-salt-in-soil-un-report-warns.

Flowers, T. J., R. Munns, and T. D. Colmer. 2015. "Sodium Chloride Toxicity and the Cellular Basis of Salt Tolerance in Halophytes." *Annals of Botany* 115, no. 3: 419–431. https://doi.org/10.1093/aob/mcu217.

Hallmark, C. T., L. P. Wilding, and N. E. Smeck. 1983. "Silicon." In *Methods of Soil Analysis: Part 2, Chemical and Microbiological Properties*, 263–273. American Society of Agronomy. https://doi.org/10.2134/agronmonogr9.2.2ed.c15.

Hassan, M. U., H. A. Kareem, S. Hussain, et al. 2023. "Enhanced Salinity Tolerance in Alfalfa Through Foliar Nano-Zinc Oxide Application: Mechanistic Insights and Potential Agricultural Applications." *Rhizosphere* 28: 100792. https://doi.org/10.1016/j.rhisph.2023.100792.

Jajoo, A. 2012. "Changes in Photosystem II in Response to Salt Stress." In *Ecophysiology and Responses of Plants Under Salt Stress*, 149–168. Springer. https://doi.org/10.1007/978-1-4614-4747-4_5.

Kilmer, V. J. 1965. "Silicon." In *Methods of Soil Analysis: Part 2, Chemical and Microbiological Properties*, 959–962. American Society of Agronomy. https://doi.org/10.2134/agronmonogr9.2.2ed.

Kraska, J. E., and G. A. Breitenbeck. 2010. "Simple, Robust Method for Quantifying Silicon in Plant Tissue." *Communications in Soil Science and Plant Analysis* 41: 2075–2085. https://doi.org/10.1080/00103624.2010.498537.

Lohaus, G., K. Pennewiss, B. Sattelmacher, M. Hussmann, and K. H. Mühling. 2001. "Is the Infiltration-Centrifugation Technique Appropriate for the Isolation of Apoplastic Fluid? A Critical Evaluation With Different Plant Species." *Physiologia Plantarum* 111: 457–465. https://doi.org/10.1034/j.1399-3054.2001.1110405.x.

Moradinezhad, F., and A. Ranjbar. 2024. "Foliar Application of Fertilizers and Plant Growth Regulators on Pomegranate Fruit Yield and Quality: A Review." *Journal of Plant Nutrition* 47, no. 5: 797–821. https://doi.org/10.1080/01904167.2023.2280152.

Pan, T., M. Liu, V. D. Kreslavski, et al. 2021. "Non-Stomatal Limitation of Photosynthesis by Soil Salinity." *Critical Reviews in Environmental Science and Technology* 51, no. 8: 791–825. https://doi.org/10.1080/10643389.2020.1735231.

Qian, J., R. Shan, Y. Shi, et al. 2024. "Zinc Oxide Nanoparticles Alleviate Salt Stress in Cotton (*Gossypium hirsutum* L.) by Adjusting Na+/K+ Ratio and Antioxidative Ability." *Life* 14, no. 5: 595. https://doi.org/10.3390/life14050595.

Rakesh, B., T. Chitdeshwari, and G. Mohanapriya. 2024. "Fascinating Role of Nanosilica in Mitigating Drought and Nutrient Stress – A Review." *Plant Stress* 14: 100672. https://doi.org/10.1016/j.stress.2024.100672.

Shabiya, A., M. A. Bhat, P. Singh, S. Hassan, and N. Hussain. 2025. "Nanofertilizers: Mechanisms, Efficacy, and Implications for Sustainable Agriculture." In *Agricultural Nutrient Pollution and Climate Change: Challenges and Opportunities*, 311–353. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-80912-5_11.

Shahzad, M., C. Zörb, C. M. Geilfus, and K. H. Mühling. 2013. "Apoplastic Na^+ in *Vicia faba* Leaves Rises After Short-Term Salt Stress and Is Remedied by Silicon." *Journal of Agronomy and Crop Science* 199: 161–170. https://doi.org/10.1111/jac.12003.

Shoukat, A., B. Pitann, M. S. Hossain, Z. A. Saqib, A. Nawaz, and K. H. Mühling. 2024. "Zinc and Silicon Fertilizers in Conventional and Nano-Forms: Mitigating Salinity Effects in Maize (*Zea mays* L.)." *Journal of Plant Nutrition and Soil Science* 187: 678–689. https://doi.org/10.1002/jpln.202300267.

Shoukat, A., B. Pitann, M. M. Zafar, et al. 2024. "Nanotechnology for Climate Change Mitigation: Enhancing Plant Resilience Under Stress Environments." *Journal of Plant Nutrition and Soil Science* 187: 604–620. https://doi.org/10.1002/jpln.202300295.

Shoukat, A., Z. A. Saqib, J. Akhtar, et al. 2024. "Zinc and Silicon Nano-Fertilizers Influence Ionomic and Metabolite Profiles in Maize to Overcome Salt Stress." *Plants* 13: 1224. https://doi.org/10.3390/plants13091224.

Singh, A., V. D. Rajput, S. Lalotra, et al. 2024. "Zinc Oxide Nanoparticles Influence on Plant Tolerance to Salinity Stress: Insights Into Physiological, Biochemical, and Molecular Responses." *Environmental Geochemistry and Health* 46: 148. https://doi.org/10.1007/s10653-024-01921-8.

Singh, N., V. Maurya, K. Gupta, et al. 2025. "Salt Stress and Its Eco-Friendly Management Using Biostimulants in Grain Legumes: A Review." *Discover Agriculture* 3, no. 1: 1–29. https://doi.org/10.1007/s44279-024-00150-y.

Steel, R. G. D., J. H. Torrie, and D. A. Dickey. 1997. *Principles and Procedures of Statistics: A Biometrical Approach*. 3rd ed. McGraw-Hill Book Co., Inc. https://doi.org/10.1002/bimj.19620040313.

Türkoğlu, A., K. Haliloğlu, M. Ekinci, et al. 2024. "Zinc Oxide Nanoparticles: An Influential Element in Alleviating Salt Stress in Quinoa (Chenopodium quinoa L. Cv Atlas)." *Agronomy* 14, no. 7: 1462. https://doi.org/10.3390/agronomy14071462.

Tuteja, N. 2007. "Mechanisms of High Salinity Tolerance in Plants." *Osmosensing and Osmosignaling*, 419–438. https://doi.org/10.1016/s0076-6879(07)28024-3.

Upadhyaya, G., and A. Roychoudhury. 2024. "Potential of Silver and Zinc Nanoparticles in Mediating Abiotic Stress Tolerance in Crop Plants." In *Metal and Metal-Oxide Based Nanomaterials: Synthesis, Agricultural, Biomedical and Environmental Interventions*, 157–177. Springer Nature. https://doi.org/10.1007/978-981-99-7673-7_8.

Wu, J., H.-P. Mock, and K. H. Mühling. 2018. "Sulfate Supply Enhances Cadmium Tolerance in *Vicia faba* L. Plants." *Environmental Science and Pollution Research* 25: 33794–33805. https://doi.org/10.1007/s11356-018-3266-6.

Yadav, A., K. Yadav, and K. A. Abd-Elsalam. 2023. "Nanofertilizers: Types, Delivery and Advantages in Agricultural Sustainability." *Agrochemicals* 2, no. 2: 296–336. https://doi.org/10.3390/agrochemicals2020019.

Zhang, R., G. Wang, S. Luo, et al. 2024. "Silicon Promotes Na^+ Compartmentalization and Mineral Uptake in Zucchini Seedlings to Maintain Physiological Homeostasis and Alleviate Salt Stress." *Journal of Plant Growth Regulation* 44: 3151–3163. https://doi.org/10.1016/j.jpowsour.2019.227610.

Zhang, Y., E. Kaiser, L. F. Marcelis, Q. Yang, and T. Li. 2020. "Salt Stress and Fluctuating Light Have Separate Effects on Photosynthetic Acclimation, but Interactively Affect Biomass." *Plant, Cell & Environment* 43, no. 9: 2192–2206. https://doi.org/10.1111/pce.13810.