Journal of Natural Resource Conservation and Management
Vol. 5, No. 2, pp 111-123, 2024
doi: 10.51396/ANRCM.5.2.2024.111-123

Growth, yield and zinc uptake by wheat in response to zinc fertilization under different saline environments

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Received : August 06, 2024
Revised : November 03, 2024
Accepted : November 06, 2024
Published : December 31, 2024

ABSTRACT

Soil salinity is a major constraint to crop production in various regions of the globe. The application of zinc (Zn) is regarded as an important practice to mitigate the adverse effects of soil salinity. Therefore, a screen house experiment was conducted with different levels of zinc (0, 5, 10 and 15 ppm) under different saline environments (EC_e 4, 8 and 12 dS m^{-1}) along with control in a completely randomized design replicated thrice on sandy soil to evaluate the impact of Zn and salinity on growth, yield and zinc uptake by wheat (*Triticum aestivum* L.). Application of zinc and artificial salinity was developed in the soil before sowing of wheat. The results highlighted that germination of wheat was delayed with increasing salinity from 4 to 12 dS m^{-1} than control and germination increased with the application of zinc. The effect of chloride dominated salinity was more prominent as compared to sulphate dominated salinity. The mean plant height of wheat decreased from 39.77 to 28.90 cm and 40.73 to 35.03 cm in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1} in chloride and sulphate dominated salinity at 0 ppm level of zinc. The reduction in chlorophyll 'a' and chlorophyll 'b' was more in case of chloride dominated salinity as compared to sulphate dominated salinity. The increased levels of Zn from 0 to 15 ppm in soil resulted in increase of both grain and straw yield by 34.1and 36.7 per cent, respectively in non-saline soil. Zinc uptake by wheat plant and grain significantly decreased with increased level of salinity. Zinc uptake by plant and grain increased with applied Zn under different saline environments. A substantial increase in grain Zn uptake was observed as the level of Zn was increased. These results suggest that Zn was protective against the salt toxicity in wheat as its application noticeably decreased the depressing effects of salinity on growth, yield and Zn uptake by wheat.

Keywords: germination, soil salinity, zinc uptake, wheat

INTRODUCTION

Soil salinity is one of the main abiotic stresses that extensively hinders crop growth both in irrigated and non-irrigated regions of the world (Ashraf *et al*., 2008; Uddin *et al*., 2009; Irakoze *et al*., 2019). Soil salinity impacts about 955 million ha which is almost 7% of the world's total arable land (Ibrahim *et al*., 2007; Singh *et al*., 2016). In India, 2% of the geographical area is occupied by salt affected soils especially in arid, semi-arid and coastal regions (Bhat *et al*., 2017); out of which 3.79 and 2.95 m ha are sodic and saline soils, respectively (Rani *et al*., 2019). Salinity not only affects germination but also crop growth and productivity (Barnwal *et al*., 2020). It is estimated that nearly half of the agricultural lands will be affected by salinity by 2050 (Shrivastava and Kumar, 2015). Consequently, it is predicted that soil salinity will cause yearly loss of about 12 billion US dollars throughout the world owing to decreased crop production (Jägermeyr and Frieler, 2018). Therefore, it is important to understand the crop response to salinity stress to minimize the economic loss besides preserving food security (Shaaban *et al.*, 2023). The harmful effects of salinity on plant growth are linked with low water potential of the root medium which is responsible for a water deficit within the plant; toxic effects of ions primarily Na^+ and Cl^- and nutritional imbalance induced by lower nutrient uptake and/or transport to the shoot (Hasegawa *et al.*, 2000). Excessive Na^+ concentration in the plant tissue hampers nutrient balance, osmotic activity and leads to specific ion toxicity (Katerji *et al.*, 2004; Arzani, 2008). Ionic imbalance is created due to the excessive concentration of ions like Na^+ and Cl^- by reducing the uptake of other beneficial ions such as Ca^{2+}, Mn^{2+} and K^+ resulting in wide range of physiological and biochemical changes that affect growth as well as development of plant (Alam *et al.*, 2004; Zadeh and Naeini, 2007). The deficiency of Zn elevates Na^+ uptake owing to its inverse effect on membrane integrity (Cakmak, 2000; Aktafi *et al.*, 2006).

Zinc is known as one of the most essential micronutrients and its deficiency is ascertained as an acute problem in plants, particularly under saline conditions with high pH values. It is a principal constituent of many vital enzymes like glutamate dehydrogenase, catalase and sulphur oxide dismutase (Li *et al.*, 2006) besides enhancing the biosynthesis of tryptophan, a precursor of auxins (Mapodzeke *et al.*, 2021). Various researchers have reported that the total uptake, accumulation as well as partitioning of nutrients within the plant is decreased by higher levels of salinity (Fernández García *et al.*, 2004). Zinc also plays a crucial role in protection against reactive oxygen species by improving the antioxidants system in the plant (Cakmak, 2000). Zn deficiency not only hampers yield and quality of plants but also is a major concern for human nutrition. Application of nutrients like zinc in small amount enhanced the yield of crop significantly (Sadeghi *et al.*, 2021). With increase in salinity, the concentration of zinc is reduced in crops like wheat, rice and pepper (Khoshgoftar *et al.*, 2006).

Wheat is the most widely cultivated food crop of the world. Wheat is an important cereal crop for the food security of South Asia and is the 2nd major staple food crop after rice (Dar *et al.*, 2019). It plays an important role in food and nutritional security. In India, wheat production was recorded as 109.59 million tonnes from an area of 31.13 million ha in 2021-22 (GoI, 2022). Wheat is moderately tolerant to salinity with no yield loss until a given threshold salinity is reached (Munns *et al.*, 2006) and it exhibits significant genotypic difference for salinity tolerance (Abbas *et al.*, 2013). In accordance to the information presented, it is hypothesized that Zn could ameliorate the harmful effects of salinity. Thus, the present investigation was attempted to assess the interactive effects of Zn and salinity on growth, yield and zinc uptake by wheat under saline conditions.

MATERIALS AND METHODS

The experiment was carried out in screen house at CCS Haryana Agricultural University, Hisar (29°46′E and 75°49′N at an elevation of 215.2 m above mean sea level) with wheat as test crop. The experimental design was factorial completely randomized design with three levels of chloride and sulphate dominated salinity (EC_e: 4, 8, and 12 dS m^{-1}) each superimposed with four levels of Zn (0, 5, 10 and 15 ppm) added as zinc sulphate compared with the non-saline control and replicated thrice. The soil for the experiment was collected from Balsamand Farm of CCS Haryana Agricultural University, Hisar. Soil was dried, mixed thoroughly and sieved to remove particles >5mm. Soil analysis was accomplished by following standard protocols and physicochemical properties of the soil are presented in Table 1. Before creating an artificial saline soil, 5 kg of air dried non-gypsiferous and non-calcareous soil was put in the plastic pots of 5 kg capacity lined with 2 layers of 400–gauge polythene sheets to avoid leakage of salt solution. From the air-dried soil, one portion was left untreated (referred to as normal soil) and remainder was used to prepare different types of saline soil EC_e 4, 8 and 12 dS m^{-1} by using the different salts. To create variable salinity of EC_e 4, 8, and 12 dS m^{-1}, saline waters were prepared artificially by dissolving 50, 105 and 152 me L^{-1} of total salts, respectively, in distilled water for chloride dominated saline soils and 60, 125 and 185 me L^{-1} of total salts, respectively for sulphate dominated saline soils. The required amounts of chloride and sulphate salts of Na, Ca and Mg used to prepare the desired saline water were added through NaCl, Na_2SO_4, $CaCl_2$, $MgCl_2$ and $MgSO_4$. The cations Na^+ and Ca^{2+}+Mg^{2+} were in the ratio of 1:1 (Na^+: Ca^++Mg^{2+}) where Ca^{2+} and Mg^{2+} were kept in the ratio of 1:3 (Table 2).

Pots were fertilized with 130 mg N kg^{-1} in the form of urea through two splits, i.e; one half at sowing and remaining half at 21 days after sowing.

Table 1. Physicochemical properties of the soil used for screen house experiment

Characteristics	Value	References
Mechanical composition (%)		Piper (1950)
Sand	93.5	
Silt	1.0	
Clay	5.5	
Texture	Sand	
pH (1:2)	8.39	Richards (1954)
Electrical conductivity (extract) [dS m^{-1}]	0.37	Richards (1954)
Saturation percentage	28.00	Richards (1954)
Organic carbon [%]	0.14	Walkley and Black (1934)
Calcium [cmol(p+)kg^{-1}]	2.50	Cheng and Bray (1951)
Magnesium [cmol(p+)kg^{-1}]	1.50	Cheng and Bray (1951)
Sodium [cmol(p+)kg^{-1}]	0.66	Richards (1954)
Chloride (me L^{-1})	10.00	Richards (1954)
Sulphate (me L^{-1})	1.20	Richards (1954)
DTPA extractable Zn (mg kg^{-1})	0.22	Lindsay and Norwell (1978)

Table 2. Details of chloride and sulphate dominated saline waters used

EC_e (dS m^{-1})	Type ofwater	Total dissolved salts (mg L^{-1})	Na^+	Ca^{2+}	Mg^{2+} (me L^{-1})	Cl^{-1}	SO_4^{-2}
				Chloride dominated salinity			
4	$Cl:SO_4$ (7:3)	50.00	25.00	6.25	18.75	35.00	15.00
8	$Cl:SO_4$ (7:3)	105.00	52.00	13.13	39.37	73.50	31.50
12	$Cl:SO_4$ (7:3)	152.00	76.00	19.00	57.00	106.40	45.60
				Sulphate dominated salinity			
4	$Cl:SO_4$ (3:7)	60.00	30.00	7.50	22.50	18.00	42.00
8	$Cl:SO_4$ (3:7)	125.00	62.50	15.63	46.89	37.50	87.50
12	$Cl:SO_4$ (3:7)	185.00	92.50	23.13	69.37	55.50	123.50

Phosphorous, copper, manganese and iron were applied as 50, 5, 10 and 15 mg kg^{-1} each through KH_2PO_4, $CuSO_4$, $MnSO_4$ and $FeSO_4$, respectively in the solution form at the time of sowing. All the nutrients were mixed thoroughly with soil before sowing. After equilibrating each salinity treatment for 4 days, ten wheat (variety, KRL-210) seeds per pot were sown and thinned to 8 plants when the plants attained 8-10 cm height. Germination of the seeds was checked until maximum seeds germinated. The pots were irrigated to field capacity with distilled water from surface and from bottom alternatively through a centrally embedded plastic feeder tube to keep the salt concentration uniform as far as possible throughout the root zone. The plant height was measured from soil surface to growing point at booting stage and before harvest of the crop with measuring scale. Chlorophyll content was estimated by the method described by Hiscox and Israelstam (1979) using Dimethyl Sulphoxide (DMSO). Photochemical efficiency/quantum yield was determined with intact plant in the pots with chlorophyll fluorometer. At harvest, shoots were cut at the soil surface. The samples were oven-dried at 60±5°C and dry matter yield was recorded. Half gram of well ground plant samples was digested with 20 ml diacid mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in in the ratio of 4:1. Zinc in the digest solution was determined by atomic absorption spectrophotometer. Statistical analysis was carried out with OPSTAT data analysis package (Sheoran *et al.*, 1998) using ANOVA for completely randomized design. The means were compared using least significant difference (LSD) at ($p \leq 0.05$) probability level.

RESULTS AND DISCUSSION

Percent germination

Germination of wheat was delayed with the increasing salinity from 4 to 12 dS m^{-1} than control and germination increased with the application of zinc. The effect of chloride dominated salinity was more prominent as compared to sulphate dominated salinity. The maximum delay in germination was observed with 12 EC_e (dS m^{-1}) chloride dominated salinity. The percent germination did not vary up to 4 dS m^{-1} in both types of salinity. Therefore, the data is presented only for 8 dS m^{-1} and 12 dS m^{-1} (Fig. 1-5). The data indicated that germination percentage varied from 20 to 30% in chloride dominated soils whereas, it ranged from 30 to 50% in the sulphate dominated soils of 4 EC_e (dS m^{-1}) at 7 days after sowing. In chloride dominated soils of 8 EC_e (dS m^{-1}), 100 per cent germination was observed at 13 days after sowing where 10 and 15 ppm zinc was applied and 15 days after sowing where 0 and 5 ppm zinc was applied and in case of 12 EC_e (dS m^{-1}), 100 per cent germination was recorded 17 days after sowing where 10 and 15 ppm zinc was applied and 19 days after sowing where 0 and 5 ppm zinc was applied. The germination exhibited significant variation in sulphate dominated salinity of 8 and 12 EC_e (dS m^{-1}) where 100 per cent germination was observed 11 and 15 days after sowing, respectively. Germination is the most sensitive stage affected by salinity, so there was delay and decline in per cent germination with increasing levels of salinity which might be ascribed to the effect of soluble salts on plasma membrane permeability that enhances inflow of exterior ions and effluence of cytosolic solutes in plant cells as a result of low water potential (Amador *et al.*, 2006). Salinity induced oxidative stress could be one of the reasons for reduction in total germination (Amor *et al.*, 2005). Seed germination is

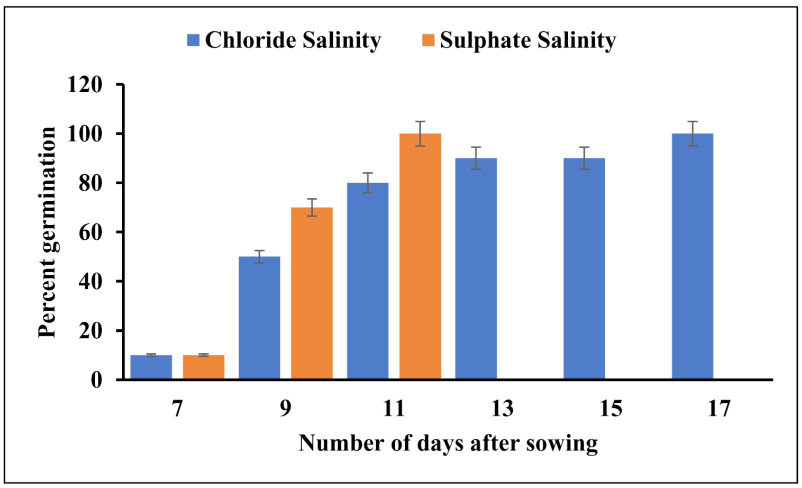

Fig. 1. Effect of salinity and zinc on percent germination of wheat in chloride and sulphate dominated salinity (8 dS m^{-1}) at 0 ppm level of zinc

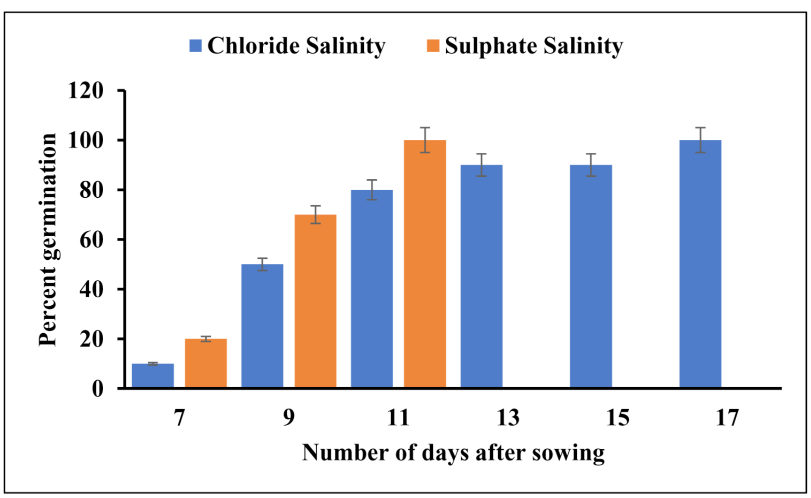

Fig. 2. Effect of salinity and zinc on percent germination of wheat in chloride and sulphate dominated salinity (8 dS m^{-1}) at 5 ppm level of zinc

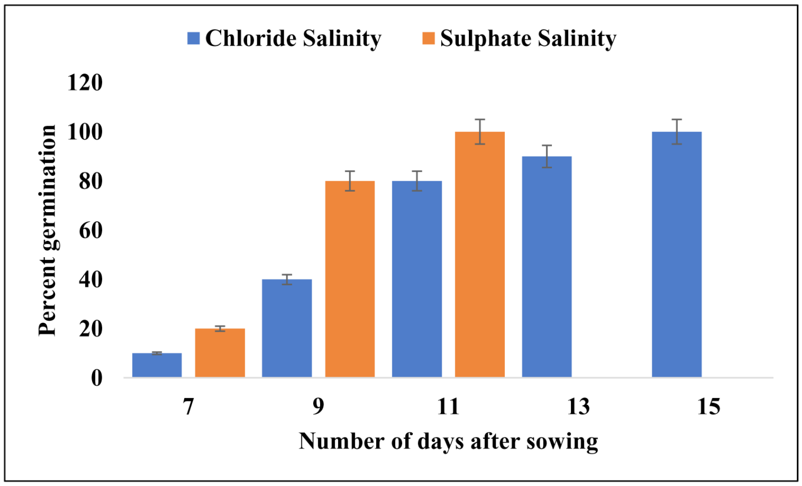

Fig. 3. Effect of salinity and zinc on percent germination of wheat in chloride and sulphate dominated salinity (8 dS m^{-1}) at 10 and 15 ppm level of zinc

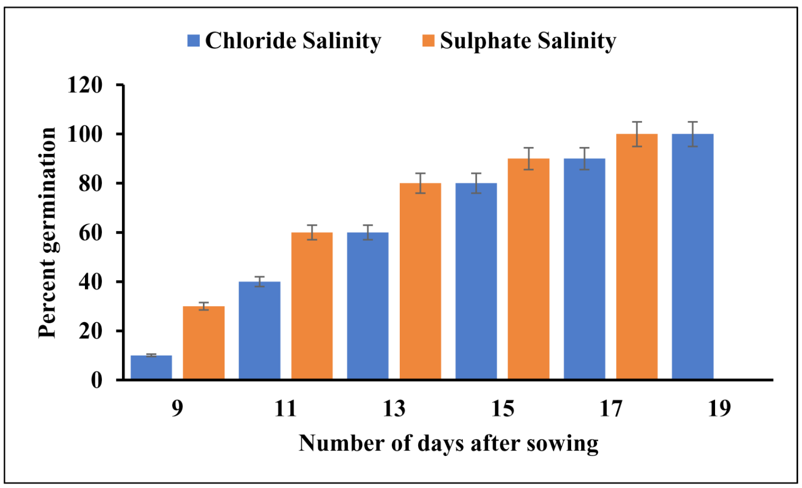

Fig. 4. Effect of salinity and zinc on percent germination of wheat in chloride and sulphate dominated salinity (12 dS m^{-1}) at 5 ppm level of zinc

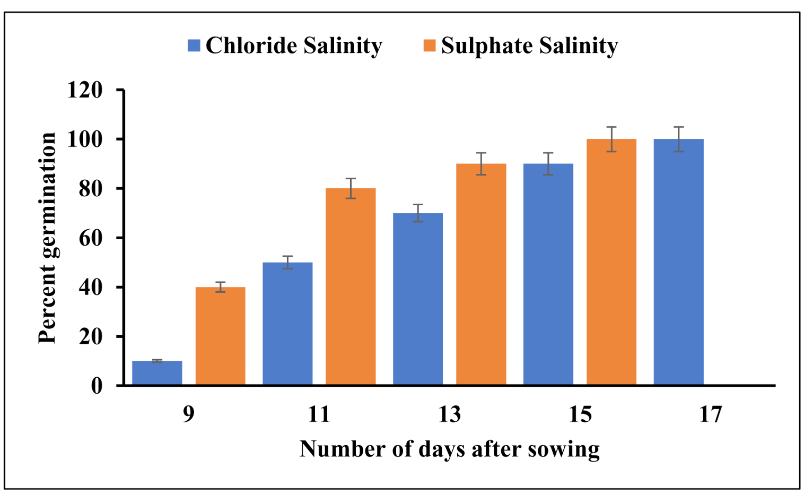

Fig. 5. Effect of salinity and zinc on percent germination of wheat in chloride and sulphate dominated salinity (12 dS m^{-1}) at 10 and 15 ppm level of zinc

inhibited as a result of ionic disturbance, osmotic and toxic effects of soluble salts (Dell'Aquila, 2000). Zinc mitigates the effect of salinity and increase the germination percentage as compared to control. Zinc showed positive effects on germination, emergence and seedling growth by increasing their concentration in seeds as reported by Harris (2008) on chickpea and wheat. Hosseini *et al.* (2002) reported the negative impact of salinity on germination characters as 81% germination diminished at 330 mM NaCl concentration, however, at 420 mM NaCl, it was merely 40% and at 500 mM NaCl there was no germination. Ahmadvand (2012) evinced that germination percentage decreased by increasing salinity levels from 4 to 8 dS m^{-1}. Bahrami and Razmjoo (2012) reported that salinity stress strongly inhibited seed germination of sesame cultivars under salinity level of 12.05 dS m^{-1}.

Plant height (cm) at booting stage and at maturity

Plant height at booting stage increased significantly from 38.23 to 43.96 cm with the increasing levels of Zn from 0 to 10 ppm in non-saline soil (Table 3). However, the plant height decreased significantly with increasing salinity levels (both chloride and sulphate dominated salinity). The mean plant height of wheat decreased from 39.77 to 28.90 cm and 40.73 to 35.03 cm in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1} in chloride and sulphate dominated salinity at 0 ppm level of zinc. The plant height increased significantly with increase in applied zinc levels from 0 to 10 ppm in soil irrespective of type and level of salinity. Mean plant height in sulphate dominated salinity was higher than in chloride dominated salinity. Mean plant height across all the salinity levels increased from 35.53 to 40.93 cm in chloride dominated salinity and 37.85 to 42.93 cm in sulphate dominated salinity as the zinc level increased from 0 to 10 ppm. The per cent decrease in mean plant height at boot stage was 23.3 to 10.5 in chloride and sulphate dominated salinity, respectively as the salinity increased from 0 to 12 dS m^{-1}. The interaction between zinc and both types of salinity was non-significant. Similar trend was observed in case of plant height at maturity as presented in Table 4. The mean plant height increased significantly from 57.10 to 63.94 cm with the increasing application of Zn from 0 to 10 ppm soil in control. Moreover, the mean plant height decreased significantly with increasing salinity levels of both chloride and sulphate dominated salinity. The mean plant height of wheat decreased from 59.17 to 49.07 cm and 59.86 to 50.04 cm in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1} at 0 ppm zinc level. The mean plant height at all salinity levels increased significantly with increase in applied zinc levels from

Table 3. Effect of salinity and zinc on plant height at booting stage (cm) of wheat

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	38.23	39.77	35.21	28.90	35.53	38.23	40.73	37.41	35.03	37.85
Zn_5	41.83	42.35	38.55	32.53	38.82	41.83	44.60	38.64	36.06	40.28
Zn_{10}	43.96	45.07	40.88	33.81	40.93	43.96	45.80	41.24	40.72	42.93
Zn_{15}	42.43	42.74	39.76	32.40	39.33	42.43	45.16	40.81	37.15	41.39
Mean	41.61	42.48	38.6	31.91		41.61	44.07	39.52	37.24	
LSD (≤5%)	Cl = 1.59; Zn = 1.58; Interaction= NS					S = 1.56; Zn = 1.55; Interaction= NS				

Table 4. Effect of salinity and zinc on plant height at maturity (cm) of wheat

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	57.10	59.17	53.58	49.07	54.73	57.10	59.86	55.24	50.04	55.56
Zn_5	61.83	62.57	60.76	51.41	59.14	61.83	64.74	61.57	54.19	60.58
Zn_{10}	63.94	64.49	62.74	53.38	61.14	63.94	67.68	63.50	57.61	63.18
Zn_{15}	61.17	62.39	58.79	46.87	57.30	61.17	65.73	58.81	52.26	59.49
Mean	61.01	62.15	58.97	50.18		61.01	64.50	59.78	53.52	
LSD (≤5%)	Cl = 1.27; Zn = 1.26; Interaction= 2.52					S = 2.04; Zn = 2.03; Interaction= NS				

0 to 10 ppm in soil. Plant height increased from 54.73 to 61.14 cm in chloride dominated salinity and 55.56 to 63.18 cm in sulphate dominated salinity. The per cent decrease in mean plant height at maturity was 11.7 and 13.3 in chloride and sulphate dominated salinity, respectively as the salinity increased from 0 to 12 dS m^{-1}. The interaction between zinc and chloride dominated salinity was significant, whereas that of zinc and sulphate dominated salinity was non-significant.

Photochemical efficiency / quantum yield (Fv/Fm)

In non-saline soil, photochemical efficiency exhibited higher values of 0.80, 0.80, 0.81 and 0.82 at the zinc levels of 0, 5, 10 and 15 ppm, respectively (Table 5). Photochemical efficiency significantly decreased with the increasing levels of salinity indicating photochemical stress. The lower photochemical efficiency was observed at the EC_e 12 dS m^{-1} in the chloride dominated salinity and the values were 0.65, 0.66, 0.67 and 0.69, whereas sulphate dominated salinity at the same EC_e resulted in photochemical efficiency of 0.68, 0.69, 0.70 and 0.71 at the zinc levels of 0, 5, 10 and 15ppm, respectively. Photochemical efficiency in chloride dominated salinity decreased from 0.81 to 0.67 whereas, in sulphate dominated salinity, it decreased from 0.81 to 0.69 as the salinity levels increased from 0 to 12 dS m^{-1}. The Fv/Fm is an important parameter, which determines the maximum quantum efficiency of photo system (PSII). The normal Fv/Fm value is usually close to 0.8 in wheat and it decreased with the increasing levels of salinity from 0 to 12 dS m^{-1}. Vaz and Sharma (2011) reported that in healthy leaves, Fv/Fm value is usually close to 0.8 in most plant species, therefore, a lower value indicates that a proportion of PSII reaction centres is damaged or inactivated, a phenomenon termed as photoinhibition, commonly observed in plants under stress. Reich *et al*. (2017) also reported decrease in Fv/Fm values with increase in salinity in *Brassica rapa* plants.

Chlorophyll 'a' and Chlorophyll 'b' (μg g^{-1} FW)

The highest chlorophyll 'a' content was observed in non-saline soil and the values were 2.45, 2.59, 2.67 and 2.78 μg g^{-1} FW at the respective zinc levels of 0, 5, 10 and 15 ppm (Table 6). The mean chlorophyll 'a' values at the EC_e 4, 8 and 12 dS m^{-1} were 2.33, 2.20 and 1.99 μg g^{-1} FW, respectively in chloride dominated salinity. However, in sulphate dominated salinity the chlorophyll 'a' values were 2.35, 2.23 and 2.07 μg g^{-1} FW, respectively where no zinc was applied. Regarding Zn levels, the higher chlorophyll 'a' content was observed at 15 ppm Zn. The chlorophyll 'a' content at EC_e 4, 8 and 12 dS m^{-1} in chloride dominated salinity was 2.54, 2.45 and 2.31 μg g^{-1} FW, respectively and in sulphate dominated salinity was 2.66, 2.55 and 2.45 μg g^{-1} FW, respectively with the application of 15 ppm Zn.

Table 5. Effect of salinity and zinc on photochemical efficiency / quantum yield (Fv/Fm) of wheat

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	0.80	0.75	0.71	0.65	0.73	0.80	0.77	0.73	0.68	0.74
Zn_5	0.80	0.76	0.72	0.66	0.74	0.80	0.79	0.74	0.69	0.76
Zn_{10}	0.81	0.77	0.73	0.67	0.74	0.81	0.79	0.76	0.70	0.76
Zn_{15}	0.82	0.77	0.74	0.69	0.75	0.82	0.80	0.78	0.71	0.78
Mean	0.81	0.76	0.72	0.67		0.81	0.79	0.75	0.69	
LSD (≤5%)	Cl = 0.001; Zn = 0.001; Interaction= NS					S = 0.01; Zn = 0.01; Interaction= NS				

Table 6. Effect of salinity and zinc on chlorophyll 'a' (μg g^{-1} FW) content of wheat

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	2.45	2.33	2.20	1.99	2.24	2.45	2.35	2.23	2.07	2.28
Zn_5	2.59	2.38	2.26	2.09	2.33	2.59	2.41	2.35	2.18	2.38
Zn_{10}	2.67	2.45	2.31	2.26	2.42	2.67	2.60	2.44	2.31	2.51
Zn_{15}	2.78	2.54	2.45	2.31	2.52	2.78	2.66	2.55	2.45	2.61
Mean	2.62	2.42	2.30	2.16		2.62	2.51	2.39	2.25	
LSD (≤5%)	Cl = 0.22; Zn = NS; Interaction= NS					S = 0.20; Zn = 0.20; Interaction= NS				

The results revealed that chlorophyll ‘a’ increased with the increasing levels of zinc from 0 to 15 ppm and decreased with the increasing levels of salinity from 0 to 12 dS m^{-1}. The higher chlorophyll ‘b’ content was observed in non-saline soil and the values were 0.48, 0.51, 0.55 and 0.59 µg g^{-1} FW at the respective zinc levels of 0, 5, 10 and 15 ppm (Table 7). The mean chlorophyll ‘b’ values at EC_e 4, 8 and 12 dS m^{-1} were 0.48, 0.46 and 0.44 µg g^{-1} FW, respectively in the chloride dominated salinity. However, in sulphate dominated salinity the chlorophyll ‘b’ values were 0.51, 0.49 and 0.46 µg g^{-1} FW, respectively. The higher chlorophyll ‘b’ values of 0.50, 50 and 0.46 µg g^{-1} FW were recorded at EC_e 4, 8 and 12 dS m^{-1} in chloride dominated salinity, respectively and in sulphate dominated salinity the values were 0.55, 0.53 and 0.49 µg g^{-1} FW, respectively.

Photosynthetic pigments i.e. chlorophyll ‘a’ and chlorophyll ‘b’ increased with the application of zinc. The decrease in chlorophyll content could be due to the fact that Na^+ may be taken up apoplastically thereby enhancing the accrual of salts in the apoplast which results in dehydration of cells or disorder of chloroplast structure and associated proteins (Jan *et al.*, 2023). Plants applied with zinc have increased photosynthetic rate due to synthesis of chloroplast, enhanced synthesis of chlorophyll, oxidation of water at PS-II, improved activities of Calvin cycle enzymes besides greater absorption of CO_2 in consequence of stomatal opening and enhanced nutrient uptake. Zinc is required for chlorophyll production as was reported by Cakmak (2008). The results are in agreement with those obtained by Eckardt (2009) who reported that during the process of chlorophyll degradation, chlorophyll ‘b’ may be converted into chlorophyll ‘a’, thus resulting in the increased content of chlorophyll ‘a’ which affect the normal ratio of chlorophyll ‘a’ and ‘b’. The salt-induced alterations in leaf chlorophyll content could be either due to inhibitory effect of salinity on synthesis and/or accelerates the degradation of existing chlorophyll molecules (Wani *et al.*, 2013).

Grain yield (g pot^{-1})

The mean grain yield increased significantly from 8.95 to 12.00 g pot^{-1} with the increasing levels of Zn from 0 to 15 ppm soil in the absence of induced salinity (Table 8). The mean grain yield at EC_e 4, 8, and 12 dS m^{-1} without zinc application was 8.12, 7.94 and 5.90 g pot^{-1}, respectively in chloride dominated salinity and respective mean grain yield in sulphate dominated salinity was 8.40, 8.17 and 6.44 g pot^{-1}. The data clearly indicated that mean grain yield decreased with increasing both types of salinity. At EC_e 4, 8 and 12 dS m^{-1} mean grain yield was 8.96, 8.35 and 6.10 g pot^{-1}, respectively in the chloride dominated salinity 9.03, 8.82 and 6.66 g pot^{-1}, respectively and in the sulphate dominated salinity with the application of 5 ppm zinc. Similarly,

Table 7. Effect of salinity and zinc on chlorophyll ‘b’ (µg g^{-1} FW) content of wheat

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	0.48	0.47	0.43	0.40	0.44	0.48	0.47	0.45	0.42	0.46
Zn_5	0.51	0.48	0.45	0.44	0.47	0.51	0.49	0.47	0.45	0.48
Zn_{10}	0.55	0.48	0.48	0.45	0.49	0.55	0.51	0.50	0.47	0.51
Zn_{15}	0.59	0.50	0.50	0.46	0.51	0.59	0.55	0.53	0.49	0.54
Mean	0.53	0.48	0.46	0.44		0.53	0.51	0.49	0.46	
LSD (≤5%)	Cl = 0.06; Zn = 0.05; Interaction= NS					S = 0.06; Zn = 0.05; Interaction= NS				

Table 8. Effect of salinity and zinc on grain yield (g pot^{-1}) of wheat

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	8.95	8.12	7.94	5.90	7.73	8.95	8.40	8.17	6.44	7.99
Zn_5	10.16	8.96	8.35	6.10	8.39	10.16	9.03	8.82	6.66	8.67
Zn_{10}	11.28	9.39	8.91	6.65	9.06	11.28	9.72	8.93	7.54	9.36
Zn_{15}	12.00	10.03	9.89	7.00	9.73	12.00	10.48	9.48	8.05	10.00
Mean	10.60	9.12	8.77	6.41		10.60	9.41	8.85	7.17	
LSD (≤5%)	Cl = 0.19; Zn = 0.18; Interaction= 0.35					S = 0.33; Zn = 0.34; Interaction= 0.66				

at the zinc level of 10 ppm with EC_e 4, 8 and 12 dS m^{-1} grain yield was 9.39, 8.91 and 6.65 g pot^{-1}, respectively in the chloride dominated salinity and 9.72, 9.83 and 7.54 g pot^{-1} in the sulphate dominated salinity. The highest mean grain yields obtained at 15 ppm zinc with 4, 8 and 12 dS m^{-1} levels were 10.03, 9.89 and 7.00 g pot^{-1}, respectively in the chloride dominated salinity and 10.48, 9.48 and 8.05 g pot^{-1} in the sulphate dominated salinity. The mean grain yield increased from 7.73 to 9.73 g pot^{-1} (25.9%) and 7.99 to 10.00 g pot^{-1} (25.2%) in chloride and sulphate dominated salinity, respectively as the zinc levels increased from 0 to 15 ppm. The results showed the positive interaction of zinc with the both types of salinity. The per cent increase in mean grain yield was 18.6 and 25.0 in chloride and sulphate dominated salinity, respectively at 12 dS m^{-1} EC_e salinity and in control it was 34.1 per cent as the zinc levels increased from 0 to 15 ppm. Plant production, mainly expressed in terms of crop yield and plant biomass or crop quality (both of vegetative and reproductive organs), is possibly affected by salinity in adverse manner which stimulate nutritional disorders such as nutrient availability, competitive uptake, transport or partitioning which may be ascribed to the effect of salinity within the plant (Zhu, 2003; Nasim *et al.*, 2008). The decrease in yield of wheat with increasing salt stress is due to reduced number of fertile florets and inhibitory effect on translocation of assimilates from shoot to panicles (Sen *et al.*, 2022).

Dry matter yield (g pot^{-1}) at booting stage and maturity

The mean dry matter yield at booting stage significantly increased from 5.08 to 5.45 g pot^{-1} (7.3%) with the increasing application of Zn from 0 to 15 ppm in the absence of induced salinity (Table 9). The mean dry matter yield of wheat decreased significantly from 4.61 to 3.68 g pot^{-1} (20.2%) and 4.78 to 3.90 g pot^{-1} (18.4%) in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1}. The mean dry matter yield across all the zinc levels increased from 4.12 to 4.75 g pot^{-1} (15.3%) and 4.33 to 4.95 g pot^{-1} (14.3%) in chloride and sulphate dominated salinity, respectively. The interaction between zinc and both types of salinity was non-significant. Similar, trend was observed in straw yield (g pot^{-1}) of wheat in relation to types of salinity and levels of zinc (Table 10). The mean straw yield increased from 10.20 to 13.94 g pot^{-1} (36.7%) with increasing the application of Zn from 0 to 15 ppm in the absence of induced salinity. Mean straw yield across all the zinc levels increased from 8.25 to 10.56 g pot^{-1} (28.0%) and 8.65 to 11.20 g pot^{-1} (29.5%) in chloride and sulphate dominated salinity, respectively. The mean straw yield at maturity increased by 36.7 per cent with increasing levels of Zn from 0 to 15 ppm in the absence of salinity. Moreover, the mean straw yield decreased significantly with increasing both chloride and sulphate dominated salinity levels. The mean straw yield of wheat across all the salinity levels

Table 9. Effect salinity and zinc on dry matter yield (g pot^{-1}) of wheat at booting stage

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	5.08	4.21	3.78	3.39	4.12	5.08	4.49	4.16	3.58	4.33
Zn_5	5.16	4.46	4.00	3.57	4.30	5.16	4.61	4.33	3.76	4.47
Zn_{10}	5.24	4.79	4.28	3.76	4.52	5.24	4.91	4.67	3.96	4.70
Zn_{15}	5.45	5.00	4.54	4.00	4.75	5.45	5.11	4.96	4.28	4.95
Mean	5.23	4.61	4.15	3.68		5.23	4.78	4.53	3.90	
LSD (≤5%)	Cl = 0.36; Zn = 0.35; Interaction= NS					S = 0.38; Zn = 0.37; Interaction= NS				

Table 10. Effect salinity and zinc on straw yield (g pot^{-1}) of wheat at harvest

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	10.2	8.88	7.35	6.58	8.25	10.20	9.40	8.23	6.76	8.65
Zn_5	11.23	9.43	7.91	6.91	8.87	11.23	10.10	8.87	7.29	9.37
Zn_{10}	13.04	10.07	9.26	7.32	9.92	13.04	11.09	9.24	7.99	10.34
Zn_{15}	13.94	10.85	9.36	8.07	10.56	13.94	12.05	10.40	8.42	11.20
Mean	12.11	9.81	8.47	7.22		12.11	10.66	9.19	7.62	
LSD (≤5%)	Cl = 0.41; Zn = 0.40; Interaction= 0.80					S = 0.56; Zn = 0.55; Interaction= NS				

decreased from 9.81 to 7.22 g pot^{-1} (26.4%) and 10.66 to 7.62 g pot^{-1} (28.5%) in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1}. The interaction of zinc and chloride was significant, whereas, interaction of zinc and sulphate was non-significant. Zinc also enhances plant productivity, leaf area and grain yield as a result of enhancing the enzymatic system of plant (Jan *et al.*, 2023).

Zn uptake at booting stage and at physiological maturity

Zinc uptake by wheat plant at booting stage increased from 57.64 to 170.62 μg pot^{-1} with increase in zinc levels from 0 to 15 ppm in the normal soil (Table 11). The increase in mean zinc uptake across all the salinity levels ranged between 40.41 to 149.76 μg pot^{-1} and 44.65 to 157.85 μg pot^{-1} in chloride and sulphate dominated salinity, respectively. The zinc uptake of the wheat at booting stage decreased with increasing levels of both types of salinity. Zinc uptake decreased by 31.69% and 27.94% in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1}. Zinc uptake by wheat straw at maturity increased from 22.89 to 141.93 μg pot^{-1} with increased levels of zinc from 0 to 15 ppm in normal soil (Table 12). The mean zinc uptake across all the zinc levels increased from 14.29 to 109.85 μg pot^{-1} and 16.66 to 123.06 μg pot^{-1} in the chloride and sulphate dominated salinity, respectively. The zinc uptake decreased by 36.6% and 29.2% in chloride and sulphate dominated salinity, respectively as the salinity levels increased from 4 to 12 dS m^{-1}. The interaction of zinc and salinity was significant showing that zinc application has a clear effect on Zn uptake. At each salinity level, in the absence of Zn application, shoot Zn concentrations of the plants were much lower than the plants treated with Zn thereby showed the importance of Zn in increasing tolerance to salt stress (Aktafi *et al.*, 2006). Zinc nutrition diminished the negative effects of salinity. When soil salinity exhibits more negative role on crop nutritional and physiological variables then sufficient inputs of Zn are advantageous to plants in dealing with salinity stress. Saeidnejad *et al.* (2016) evinced that zinc concentration in plant exhibited an increasing trend with increase in Zn levels and collective effect of zinc and salinity demonstrated the decreasing trend of Zn accumulation in wheat plants. Dogra *et al.* (2014) reported that the application of zinc had significant effect on zinc concentration in both grain and straw.

Zn uptake by grain

Zinc uptake by wheat grains also observed the similar trend as the wheat straw (Table 13). Zinc uptake increased from 60.0 to 155.67 μg pot^{-1} with increase in levels of zinc from 0 to 15 ppm in normal soils. The mean zinc uptake across all the salinity

Table 11. Effect salinity and zinc on zinc uptake (μg pot^{-1}) by wheat plants at booting stage

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	57.64	44.01	34.33	24.66	40.41	57.64	53.28	39.03	28.65	44.65
Zn_5	113.96	78.80	67.68	45.16	76.40	113.96	99.13	89.28	50.68	88.26
Zn_{10}	149.52	102.68	98.89	72.67	105.94	149.52	120.34	109.36	98.62	119.46
Zn_{15}	170.62	160.31	148.08	120.02	149.76	170.62	166.75	155.28	138.75	157.85
Mean	122.93	96.45	87.25	65.88		122.93	109.88	98.24	79.18	
LSD (≤5%)	Cl = 4.81; Zn = 4.80; Interaction= 9.61					S = 8.06; Zn = 8.05; Interaction= NS				

Table 12. Effect salinity and zinc on zinc uptake (μg pot^{-1}) by wheat straw

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	22.89	13.49	11.32	9.44	14.29	22.89	16.43	14.48	12.84	16.66
Zn_5	48.54	21.60	18.66	17.83	26.66	48.54	27.40	19.40	18.48	28.46
Zn_{10}	81.44	64.93	50.78	32.57	57.43	81.44	68.42	55.44	53.02	64.58
Zn_{15}	141.93	119.28	99.04	79.15	109.85	141.93	135.33	124.08	90.91	123.06
Mean	73.70	54.83	44.95	34.75		73.70	61.89	53.35	43.81	
LSD (≤5%)	Cl = 2.34; Zn = 2.33; Interaction= 4.67					S = 2.03; Zn = 2.02; Interaction= 4.06				

Table 13. Effect salinity and zinc on zinc uptake (µg pot^{-1}) by wheat grains

Zn levels	Chloride Salinity (dS m^{-1})					Sulphate Salinity (dS m^{-1})				
(ppm)	0	4	8	12	Mean	0	4	8	12	Mean
Zn_0	60.00	38.00	21.33	17.00	34.08	60.00	47.33	27.67	22.33	39.33
Zn_5	76.67	61.67	51.33	46.67	59.08	76.67	73.33	58.33	52.67	65.25
Zn_{10}	131.00	109.67	94.00	79.00	103.42	131.00	115.67	104.67	93.67	111.25
Zn_{15}	155.67	129.33	110.33	94.33	122.42	155.67	143.00	120.33	113.33	133.08
Mean	105.83	84.67	69.25	59.25		105.83	94.83	77.75	70.50	
LSD (≤5%)	Cl = 8.80; Zn = 8.81; Interaction= NS					S = 10.86; Zn = 10.85; Interaction= NS				

levels increased from 34.08 to 122.42 µg pot^{-1} and 39.33 to 133.08 µg pot^{-1} in the chloride and sulphate dominated salinity, respectively as the zinc level increased from 0 to 15 ppm. The Zn uptake decreased from 84.67 to 59.25 and 94.83 to 70.50 µg pot^{-1} in chloride and sulphate dominated salinity, respectively as the salinity increased from 4 to 12 dS m^{-1}. The lower uptake of Zn under salinity stress could be adduced to restricted nutrient absorption as a result of lack of nutrients due to low water potential in the rhizosphere (Tabatabei, 2006). Moradi and Jahanban (2018) also reported lower Zn uptake with increasing levels of salinity in rice. Wei *et al.* (2007) demonstrated that mobility and uptake of zinc in soil depends on various factors for instance soil pH, total value of zinc in the soil, organic matter, soil type and levels of phosphorus in the soil. Zn accumulation showed decreased trend under salinity stress. Zinc application substantially decreases the damage caused by salinity owing to its positive effects on the uptake and partitioning of important mineral elements (Weisany *et al.*, 2014).

CONCLUSION

Zinc was protective against the salt toxicity in wheat and its application markedly reduced the depressing effects of high salinity on germination by enhancing the per cent germination and its uptake in wheat. The interaction of salinity and Zn caused a significant agronomic and physiological responses in wheat which mitigate the negative consequences of stress. That was possible due to the physiological and biochemical alterations induced by the application of Zn in plants. Therefore, to have optimum wheat grain yield grown in saline soils application of Zn is necessary. These results might be regarded as a nutrient management tool particularly for plants under salinity stress.

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