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Effect of Foliar Application of Salicylic Acid on Enhancing Salinity Tolerance in Sorghum (*Sorghum bicolor* L.)

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Abstract

Salinity represents a major abiotic constraint that adversely affects crop productivity, particularly in arid and semi-arid regions. Under saline conditions, plant growth and development are primarily hindered by physiological drought, ionic toxicity resulting from excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions, and the generation of reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, hydroxyl ions, and singlet oxygen within chloroplasts, mitochondria, and the apoplastic space. To address the impact of salinity stress, a field experiment was conducted during the Kharif seasons of 2023, 2024, and 2025 at a farmer's field in Kakarlamoodi village. The objective was to evaluate the efficacy of foliar application of salicylic acid in enhancing salinity tolerance in sorghum. The study was structured using a randomized block design comprising six treatments, each replicated four times. Five concentrations of salicylic acid (50, 100, 150, 200, and 250 mg L^{-1}) were applied, along with a control treatment. The results demonstrated that the 250 mg L^{-1} salicylic acid treatment significantly improved grain yield (5729, 6235 and 6300 kg ha^{-1}), whereas the lowest yield was recorded under the control treatment. In addition to yield enhancement, the highest values for total chlorophyll content, antioxidant enzyme activity, protein concentration, and potassium accumulation in both grain and straw were observed with the 250 mg L^{-1} foliar application, indicating its effectiveness in mitigating the adverse effects of salinity.

Keywords: Anti–oxidant activity, Carotenoids, Chlorophyll, Proline, Salinity, Salicylic acid

Introduction

Salinity is recognized as a major abiotic stressor that adversely affects crop productivity, particularly in arid and semi-arid regions (Sytar *et al.*, 2017). Globally, approximately 19.5% of irrigated lands and 2.1% of drylands are impacted by salinity, a condition that continues to worsen due to improper irrigation practices (Shrivastava and Kumar, 2015). As a result, many farmers leave salt-affected soils uncultivated, citing poor economic returns and reduced yields. The management of such soils poses significant challenges, primarily due to elevated cultivation costs and limited crop performance. Excessive salt concentrations in soil disrupt plant physiology by inducing hyperosmotic stress, ionic imbalance, nutrient deficiencies, and the accumulation of reactive oxygen species (ROS), which collectively impair cellular functions and hinder growth. Plants respond to these conditions by activating antioxidant defense systems, which help mitigate oxidative damage (Spychalla and Desborough, 1990). Additionally, they accumulate osmo-protective compounds such as carbo-hydrates, amino acids, proline, and proteins to stabilize cellular structures, maintain vacuolar ionic balance, and neutralize free radicals (Singh *et al.*, 2015). Proline, a nonessential amino acid, plays a multifaceted role in stress tolerance. Its accumulation contributes to osmotic adjustment, enzyme protection, membrane stabilization, and ROS scavenging (Verbruggen and Herman, 2008). This regulation supports water uptake, cell turgor maintenance, and the continuity of vital physiological processes, including photosynthesis and growth (Turner, 2018).

Maintaining ionic homeostasis, particularly the Na^+/K^+ ratio, is essential for plant survival under saline conditions (Gupta and Huang, 2014). Plants employ mechanisms such as selective ion uptake and compartmentalization to reduce the toxic effects of sodium and chloride ions. These ions are either sequestered into vacuoles or redistributed to less sensitive tissues, thereby minimizing damage to critical cellular components. The salt overly sensitive (SOS) signaling pathway plays a pivotal role in regulating ion transporters and maintaining ionic equilibrium under salt stress. Among the strategies to counteract salinity, the exogenous application of plant growth regulators has emerged as a practical and effective approach (Quamruzzaman *et al.*, 2021). Salicylic acid (SA), a phenolic compound, functions as a growth regulator, modulating various physiological processes, including seed germination, ion transport, membrane permeability, stomatal behavior, transpiration, and photosynthesis (Saleem *et al.,* 2021; Singh *et al.,* 2021). SA also enhances plant resilience to environmental stressors, including salinity, by activating defense pathways and stabilizing cellular functions (Yu *et al.,* 2020). Numerous studies have demonstrated the efficacy of SA in alleviating salt-induced stress (Noreen *et al.*, 2016). It has been identified as a potent phyto-protectant that mitigates osmotic and ionic disturbances, promoting salt tolerance across diverse plant species. While genetic modification and breeding programs offer long-term solutions for developing salt-tolerant cultivars, these approaches are often complex and time-intensive. In contrast, chemical interventions such as the foliar application of growth regulators, fertilizers, and non-enzymatic antioxidants offer a more immediate and accessible means of enhancing plant performance under saline conditions, particularly when endogenous hormone levels are suppressed during stress.

Material and Methods

A field experiment was conducted over three consecutive *Kharif* seasons (2023 to 2025) at farmer's field located in Kakarlamoodi village. The experimental site featured clay-textured soil with a neutral pH of ~7.5 and low electrical conductivity (~0.24 dS m^{-1}). The soil was characterized by medium levels of organic carbon, low available nitrogen, moderate phosphorus availability, and high potassium content. The study employed a randomized block design comprising six treatments, each replicated four times. Foliar application of salicylic acid was administered at five concentrations (50, 100, 150, 200, and 250 mg L^{-1}), along with a control treatment without application of salicylic acid. Nitrogen was supplied in the form of urea and applied in three equal splits: at sowing (basal), at the knee-height stage, and at flowering. Phosphorus (60 kg ha^{-1}) and potassium (40 kg ha^{-1}) were uniformly applied to all plots as basal doses using single super phosphate (SSP) and muriate of potash (MOP), respectively, during the *Rabi* seasons of 2023 and 2024. Irrigation and weed control measures were implemented as needed throughout the crop cycle. Statistical analysis of the collected data was performed using the methodology outlined by Panse and Sukhatme (1978), with significance determined at the 5 percent probability level.

Results and Discussion

Across the 2023 to 2025 study period, plant height in sorghum was not significantly affected by varying concentrations of salicylic acid. However, key yield attributes responded positively to the treatments. Notably, the longest ear head lengths (32.7 cm, 35.5 cm, and 35.1 cm) were consistently recorded under the 250 mg L^{-1} salicylic acid application. These values were significantly greater than those observed in the control and the 50 mg L^{-1} treatment, while remaining statistically comparable to other intermediate concentrations during all three years. These findings are consistent with previous research, such as Jangra *et al.* (2023), which documented improvements in panicle length and the number of productive structures in salicylic acid-treated plants grown under saline conditions. In contrast, no significant variation was observed in the test weight of sorghum across treatments, indicating that while morphological traits such as ear head length were enhanced, seed weight remained unaffected (Table 1).

The study demonstrated that varying concentrations of salicylic acid applied foliarly had a significant effect on both grain and straw yields in sorghum. The highest grain yields (5729,

Table 1. Effect of foliar application of salicylic acid on yield attributes of Sorghum crop

Treatments	Plant height (cm)			Ear head length (cm)			Test weight (g)		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	132.0	137.9	161.2	29.8	31.9	30.7	33.4	31.4	31.0
T_2	131.0	140.9	162.1	30.0	33.9	31.0	33.4	32.4	32.8
T_3	135.5	134.9	163.7	32.3	34.2	32.7	34.2	31.6	33.1
T_4	135.0	139.3	165.7	32.4	34.4	33.5	34.6	35.1	34.6
T_5	134.3	139.5	168.0	31.0	35.1	34.2	34.9	34.5	34.0
T_6	134.8	138.9	170.7	32.7	35.5	35.1	35.8	33.6	34.2
SEm +	2.64	3.59	4.8	0.85	0.84	1.3	1.3	1.9	1.4
LSD (p=0.05)	NS	NS	NS	2.6	2.5	3.9	NS	NS	NS
CV (%)	5.9	5.2	5.9	10.4	12.0	7.9	11.8	11.7	9.6

Treatments T_1 to T_6 represent control and five concentrations (50, 100, 150, 200, and 250 mg L^{-1}) of foliar application of salicylic acid, respectively

6235, and 6300 kg ha^{-1}) were achieved with the 250 mg L^{-1} treatment, which showed statistical equivalence with the 150 and 200 mg L^{-1} treatments, yet remained significantly superior to all other treatments. The control group consistently recorded the lowest grain yields (4314, 4768, and 4875 kg ha^{-1}) across the study period. A similar pattern was observed in straw yield, with the 250 mg L^{-1} treatment producing the highest stover yields (7223, 7731, and 8800 kg ha^{-1}), while the control treatment (T_1) yielded the lowest values during all three years. These results affirm the role of salicylic acid in enhancing biomass production under stress conditions. Dehnavi *et al*. (2022) and Jangra *et al*. (2023) reported improvements in yield, chlorophyll retention, and assimilate transport in plants treated with salicylic acid under saline environments. Likewise, Hanif *et al.*, (2024) and Jangra *et al.* (2023) observed increased grain yield and spikelet fertility in barley and sorghum, respectively, following foliar application of salicylic acid in salt-affected soils. No statistically significant differences were observed in the harvest index among the treatments, indicating that while biomass and yield were enhanced, the proportion of economic yield relative to total biomass remained stable (Table 2).

Varying concentrations of salicylic acid applied foliarly had a significant impact on chlorophyll composition in sorghum. The highest levels of chlorophyll-a (1.62, 1.79, and 1.71 mg g^{-1}), chlorophyll-b (0.08, 0.88, and 0.84 mg g^{-1}), and total chlorophyll (2.46, 2.69, and 2.58 mg g^{-1}) were consistently recorded under the T_6 treatment, corresponding to 250 mg L^{-1} of salicylic acid. Chlorophyll-a and total chlorophyll contents under T_6 were significantly higher than those

Table 2. Effect of exogenous application of salicylic acid on yield and harvest index of Sorghum crop

Treatments	Grain yield (kg ha^{-1})			Stover yield (kg ha^{-1})			Harvest index (%)		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	4314	4768	4875	5805	6007	7025	42.6	44.2	41.0
T_2	4476	4900	5113	5960	6370	7350	42.8	43.5	41.0
T_3	4982	5100	5300	6173	6477	7500	43.1	44.1	41.4
T_4	5251	5535	5588	6445	6974	7788	43.3	44.2	41.8
T_5	5487	5800	6125	6680	7192	8375	43.7	44.6	42.2
T_6	5729	6235	6300	7223	7731	8800	44.2	44.6	41.8
SEm +	248.0	321.3	314.7	390	404.8	394.3	1.1	1.2	1.0
LSD (p=0.05)	744	968	949	1170	1220.1	1189	NS	NS	NS
CV (%)	16.5	11.9	11.3	11.6	11.9	10.1	5.2	5.3	6.9

Treatments as in Table 1

observed in T_1 through T_4 treatments, while chlorophyll-b content under T_6 surpassed all other treatments (Table 3). The control group exhibited the lowest chlorophyll concentrations across all parameters. These results are consistent with previous studies, such as Dehnavi *et al.* (2022), which reported enhanced chlorophyll retention, structural integrity of chloroplasts, and increased antioxidant enzyme activity in sorghum exposed to salinity stress following salicylic acid application. The role of photosynthesis as a central metabolic pathway in plant development is well established, and its sensitivity to salinity stress has been documented by Leegood (2006) and Pan *et al.* (2021), highlighting its importance as a physiological target for mitigating salt-induced damage.

The foliar application of salicylic acid significantly influenced antioxidant enzyme activity in sorghum, particularly with respect to proline accumulation, peroxidase activity, and total phenolic content. The highest proline concentrations (1.45, 1.29, and 1.37 mg g^{-1}) were consistently recorded under the 250 mg L^{-1} salicylic acid treatment, which outperformed all other treatments across the study years (Table 4). Peroxidase activity was also maximized under the T_6 treatment, followed sequentially by T_5, T_4, and T_3, with statistically significant differences compared to T_2 and the control (T_1). The lowest peroxidase activity values (3.0, 3.7, and 3.4 O.D./min/g) were observed in the untreated control group during the study period. Similarly, total phenolic content reached its peak under T_6 (89.3%, 76.2%, and 82.8%), showing significant superiority over all other treatments, including the control (41.9%, 39.5%, and 40.7%). This enhancement was statistically comparable only to T_5 during the same timeframe. These biochemical improvements suggest enhanced osmotic

Table 3. Effect of exogenous application of salicylic acid on chlorophyll contents of Sorghum crop

Treatments	Chlorophyll-a (mg g^{-1})			Chlorophyll-b (mg g^{-1})			Total chlorophyll (mg g^{-1})		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	1.20	1.11	1.16	0.60	0.53	0.57	1.71	1.63	1.67
T_2	1.21	1.14	1.18	0.61	0.56	0.59	1.82	1.71	1.77
T_3	1.29	1.23	1.26	0.64	0.62	0.63	1.94	1.86	1.90
T_4	1.37	1.39	1.38	0.65	0.70	0.68	2.02	2.09	2.06
T_5	1.53	1.62	1.58	0.72	0.81	0.77	2.25	2.43	2.34
T_6	1.62	1.79	1.71	0.80	0.88	0.84	2.46	2.69	2.58
SEm +	0.03	0.09	0.06	0.03	0.03	0.03	0.14	1.66	0.90
LSD p=(0.05)	0.09	0.27	0.18	0.09	0.08	0.09	0.43	0.5	0.47
CV (%)	15.3	14.3	12.8	9.6	9.5	7.6	11.5	12.5	10.0

Treatments as in Table 1

Table 4. Effect of exogenous application of salicylic acid on anti-oxidant enzyme activity of Sorghum crop

Treatments	Proline content (mg g^{-1})			Peroxidase activity (O.D/min/g)			Total phenols (%)		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	0.41	0.53	0.47	3.0	3.7	3.4	41.9	39.5	40.7
T_2	0.55	0.68	0.62	3.4	3.9	3.7	49.6	45.2	47.4
T_3	0.65	0.79	0.72	3.7	4.2	4.0	60.1	51.7	55.9
T_4	0.66	0.86	0.76	3.7	4.3	4.0	73.9	59.7	66.8
T_5	0.84	0.95	0.90	3.8	4.5	4.2	84.2	68.2	76.2
T_6	1.45	1.29	1.37	3.9	4.6	4.3	89.3	76.2	82.8
SEm +	0.06	0.11	0.08	0.14	0.13	0.1	3.77	3.8	3.8
LSD (p=0.05)	0.18	0.32	0.25	0.4	0.4	0.4	11.4	11.6	11.5
CV (%)	14.6	9.6	12.10	12.4	14.1	13.3	11.3	13.5	12.4

Treatments as in Table 1

Table 5. Effect of exogenous application of salicylic acid on protein and carotinoid contents of Sorghum crop

Treatments	Protein content in grain (mg g^{-1})			Protein content in straw (mg g^{-1})			Carotinoids (mg g^{-1})		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	5.2	6.7	6.0	2.6	2.4	2.5	0.16	0.57	0.37
T_2	5.5	7.3	6.4	2.9	3.6	3.3	0.25	0.66	0.46
T_3	6.0	7.5	6.8	3.6	4.0	3.8	0.50	0.70	0.60
T_4	6.3	8.1	7.2	4.0	4.2	4.1	0.54	0.72	0.63
T_5	6.8	8.4	7.6	4.2	4.6	4.4	0.60	0.76	0.68
T_6	7.3	9.6	8.5	4.6	4.9	4.8	0.61	0.85	0.73
SEm +	0.27	0.4	0.3	0.22	0.3	0.3	0.02	0.04	0.03
LSD (p=0.05)	0.81	1.3	1.1	0.68	0.8	0.7	0.05	0.13	0.09
CV (%)	12.7	10.9	11.8	12.2	11.8	12.0	11.4	12.1	10.7

Treatments as in Table 1

regulation and a strengthened antioxidative defense system. Supporting literature suggests that the application of salicylic acid under saline conditions promotes the accumulation of proline, elevates peroxidase activity, and increases the production of phenolic compounds in crops such as sorghum and soybean (Dehnavi *et al.,* 2022; Jaiswal *et al.*, 2014). These physiological responses are attributed to the activation of stress-responsive genes, stimulation of the phenylpropanoid biosynthetic pathway, and improved reactive oxygen species (ROS) detoxification. Earlier work by Durner and Klessig (1996) also highlighted salicylic acid's role in enhancing both enzymatic and non-enzymatic antioxidant mechanisms.

The application of salicylic acid at varying concentrations had a significant impact on both protein and carotenoid levels in sorghum grain and straw. The highest protein concentrations were recorded in grain (7.3%, 9.6%, and 8.5%) and straw (4.6, 4.9, and 4.8 mg g^{-1}) under the T_6 treatment (Table 5). Grain protein levels under T_6 were statistically comparable to those observed in T_5, while straw protein content showed parity with both T_5 and T_4 treatments. These values were notably superior to those recorded in the remaining treatments throughout the study period. Previous research supports these findings. For instance, Amini and Ehsanpour, (2005) observed increased soluble protein levels in tomato leaves and stems under saline conditions following salicylic acid application. Similarly, El-Tayeb, (2005) reported enhanced protein and amino acid synthesis in maize subjected to salt stress when treated with salicylic acid. Carotenoid content was also significantly influenced, with the highest values (0.61, 0.85, and 0.73 mg g^{-1}) observed in T_6, followed by T_5. The control treatment consistently showed the lowest carotenoid concentrations (0.16, 0.57, and 0.37 mg g^{-1}). Hanif *et al.* (2024) further corroborated these results, noting that salicylic acid application in rice improved protein and carotenoid accumulation by enhancing nitrogen metabolism and stabilizing pigment integrity.

The exogenous application of salicylic acid had a marked effect on the sodium and potassium concentrations in both grain and straw of sorghum. The highest potassium levels in grain (0.89%, 0.90%, and 0.82%) and straw (1.07%, 1.13%, and 1.10%) were recorded under the T_6 treatment (Table 6). These values were statistically comparable to those observed in T_5, T_4, and T_3 for grain, and to T_5 and T_4 for straw, while remaining significantly higher than those in all other treatments. Conversely, the lowest sodium concentrations in grain (0.10%, 0.14%, and 0.26%) and straw (0.15%, 0.13%, and 0.14%) were also associated with T_6, which demonstrated a statistically significant reduction compared to all other treatments. The highest sodium accumulation was noted in the control group (T_1), with grain values of 0.23%, 0.25%, and 0.30%, and straw values of 0.28%, 0.23%, and 0.26%.

Experimental data demonstrated that the highest potassium-to-sodium (K^+/Na^+) ratios in both grain (8.30, 6.43, and 7.62) and straw (7.44,

Table 6. Effect of exogenous application of salicylic acid on sodium, potassium contents of Sorghum crop

Treatments	K content in grain (%)			K content in straw (%)			Na content in grain (%)			Na content in straw (%)		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	0.75	0.74	0.76	0.84	0.88	0.9	0.23	0.25	0.30	0.28	0.23	0.26
T_2	0.81	0.79	0.78	0.89	1.01	1.0	0.19	0.23	0.30	0.26	0.19	0.23
T_3	0.85	0.82	0.80	0.93	1.06	1.0	0.17	0.19	0.28	0.21	0.17	0.19
T_4	0.86	0.85	0.81	0.97	1.08	1.0	0.15	0.17	0.27	0.21	0.16	0.19
T_5	0.88	0.86	0.81	0.98	1.10	1.0	0.13	0.16	0.27	0.16	0.14	0.15
T_6	0.89	0.90	0.82	1.07	1.13	1.1	0.10	0.14	0.26	0.15	0.13	0.14
SEm +	0.02	0.03	0.03	0.03	0.01	0.0	0.01	0.01	0.02	0.01	0.01	0.01
LSD (p=0.05)	0.07	0.10	0.1	0.10	0.2	0.2	0.02	0.04	0.1	0.02	0.03	0.03
CV (%)	5.5	7.3	13.8	6.7	10.6	8.7	8.4	14.2	17.4	7.2	13.1	10.15

Treatments as in Table 1

Table 7. Effect of exogenous application of salicylic acid on sodium, potassium contents, and K^+/Na^+ ratio of Sorghum crop

Treatments	K^+/Na^+ ratio in grain			K^+/Na^+ ratio in straw		
	2022-23	2023-24	2024-25	2022-23	2023-24	2024-25
T_1	3.31	2.98	7.20	3.05	3.90	3.5
T_2	4.37	3.48	7.27	3.51	5.33	4.4
T_3	4.97	4.43	7.43	4.46	6.26	5.4
T_4	5.78	5.15	7.52	4.65	6.79	5.7
T_5	7.03	5.40	7.52	6.13	8.01	7.1
T_6	8.30	6.43	7.62	7.44	8.72	8.1

8.72, and 8.10) were consistently recorded in plants treated with salicylic acid at a concentration of 250 mg L^{-1} (Table 7). In contrast, the control group exhibited the lowest values across these parameters throughout the study period. Under saline conditions, the rate of photosynthesis showed a strong positive correlation with stomatal behavior, pigment concentration, and ionic balance, particularly the K^+/Na^+ ratio. These findings align with previous research indicating that exogenous application of salicylic acid under salt stress enhances photosynthetic efficiency by modulating stomatal conductance and stabilizing pigment composition (Noreen *et al.*, 2016). Comparable outcomes were reported by Sofy *et al.* (2020), who found that foliar application of salicylic acid significantly mitigated sodium chloride toxicity by promoting potassium uptake and improving the K^+/Na^+ ratio. Furthermore, studies by Mundada *et al.* (2021) and Chai *et al.* (2010) suggest that proline accumulation during salt stress may contribute to reduced absorption of harmful ions by lowering cellular osmotic potential, a relationship supported by the observed positive correlation between proline levels and K^+/Na^+ ratios. The analysis indicated that foliar application of salicylic acid had a significant impact on economic performance indicators, including gross returns, net returns, and the benefit-cost ratio. Among the treatments, T_6 yielded the most favorable outcomes across all three parameters, followed closely by T_5. In contrast, the control treatment consistently recorded the lowest values for gross and net returns as well as the benefit-cost (BC) ratio (Table 8).

Table 8. Effect of exogenous application of salicylic acid on economics of Sorghum crop

Treatments	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	BC ratio
T_1	94908	47408	1.0
T_2	98472	50972	1.1
T_3	109604	62104	1.3
T_4	115522	68022	1.4
T_5	120714	73214	1.5
T_6	126038	78538	1.7

Treatments as in Table 1

Conclusion

The findings of this study indicate that under saline conditions, foliar application of salicylic acid elicits a physiological adaptation in sorghum, mitigating the detrimental effects of salt stress. Specifically, SA treatment promoted the accumulation of proline and enhanced the activity of key antioxidant enzymes, thereby safeguarding the photosynthetic apparatus. This protective mechanism contributed to the preservation of photosynthetic efficiency and supported overall plant growth. The extent of SA-induced stress alleviation was found to be concentration-dependent, with 250 mg L^{-1} emerging as the most effective dosage for counteracting salinity-induced damage. These results suggest that the foliar application of SA can be strategically employed to modulate photosynthetic performance, antioxidant defense, and ionic balance, particularly the potassium-to-sodium ratio, in sorghum cultivated under saline conditions.

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