



Optimizing spinach production in arid regions by integrating soil and foliar applications of micronutrients with organic fertilizers under saline irrigation

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Summary

This study aimed to optimize integrated nutrient management (INM) strategies to enhance the growth, yield, and biochemical composition of spinach under varying irrigation water salinity levels. A field experiment comprising twelve treatments was conducted using combinations of irrigation salinity (0.5, 2.0, and 4.0 dS/m EC), recommended dose of fertilizers (RDF), organic amendments (farmyard manure and vermicompost), and micronutrient applications (soil and foliar). The untreated control (T1), irrigated with 4.0 dS/m EC water alone, recorded the lowest plant height, leaf number, leaf area, dry matter, and yield, confirming the adverse impact of high salinity. In contrast, integrated nutrient treatments significantly improved spinach performance. The most favorable results were observed in Treatment 12 (0.5 dS/m EC + RDF + 50% FYM + 50% VC + foliar ZnSO₄ @ 0.5% + soil FeSO₄ @ 0.5%), which recorded the highest plant height (29.13 cm), leaf number (15.8), leaf area (11.45 cm² at 45 DAS; 16.76 cm² at 60 DAS), dry matter (6.89%), total soluble solids (6.77%), and total yield (266.8 kg/ha). Treatment 4, with 4.0 dS/m EC water and full INM inputs, showed comparable performance (yield: 261.2 kg/ha; plant height: 28.59 cm), highlighting INM's potential under salinity stress. Biochemical analysis revealed that Treatment 3 (4.0 dS/m EC + RDF + 100% FYM + FeSO₄ @ 0.5%) showed the highest chlorophyll a (0.754 mg/g), chlorophyll b (0.293 mg/g), carotenoids (0.515 mg/g), and ascorbic acid (29.97 mg/100g). Overall, optimized INM effectively mitigates salinity stress, enhances physiological and biochemical traits, and promotes sustainable spinach cultivation in saline-prone areas.

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Introduction

Spinach (*Spinacia oleracea* L.) is a highly nutritious leafy vegetable, valued for its rich content of essential micronutrients such as vitamins A and C, iron, calcium, and folate. Its rapid growth cycle, adaptability to a wide range of climatic conditions, and high economic returns make it particularly suitable for cultivation in arid and semi-arid regions. These regions, however, are increasingly challenged by declining soil fertility, nutrient depletion, and severe water scarcity, which collectively threaten sustainable agricultural productivity (Meena et al. 2021; Haldhar & Maheshwari 2021). One of the most pressing issues in arid agro-ecosystems is soil degradation, characterized by erosion, declining organic matter, and imbalanced fertilization practices. These factors contribute to diminished soil fertility and overall productivity (Haldhar et al. 2018). Compounding these issues is the progressive salinization of irrigation water, primarily resulting from the over-extraction of groundwater and limited access to high-quality freshwater sources (Samadia & Haldhar 2019; Meena et al. 2025). Salinity stress impacts plants by inducing osmotic stress, causing ion toxicity (especially from Na⁺ and Cl⁻), and creating nutrient imbalances that interfere with water uptake, metabolic processes, and overall

growth (Francois et al. 1994).

Globally, freshwater scarcity is intensifying due to climate change, erratic precipitation patterns, and excessive exploitation of water resources. Consequently, there is increasing reliance on non-conventional irrigation sources such as saline groundwater and treated wastewater, particularly in water-limited environments. While these alternatives provide temporary relief, they also pose long-term risks, including salt accumulation in the root zone and degradation of soil structure and fertility. Salinity-induced stress reduces nutrient uptake efficiency, inhibits enzyme function, and accelerates leaf senescence, ultimately undermining vegetable production (Jamil et al. 2006; Qadir et al. 2004).

Although spinach demonstrates moderate salinity tolerance, its yield and nutritional quality are significantly affected under high salinity conditions. Studies have shown that the negative effects of salinity can be mitigated through adaptive soil management strategies, particularly Integrated Nutrient Management (INM) (Francois et al. 1994; Qadir et al. 2004; Bhatti et al. 2015).

INM is a sustainable and holistic approach that involves the combined use of inorganic fertilizers, organic amendments, and micronutrients delivered via soil and foliar application. This integrated strategy ensures a

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balanced nutrient supply, improves soil health, and enhances crop performance under stress conditions. Foliar application of micronutrients has been proven effective in overcoming the limitations of root nutrient uptake in saline soils. By delivering essential elements directly to leaf tissues, foliar sprays enhance chlorophyll synthesis, improve ionic balance (e.g., K^+/Na^+ ratio), and activate antioxidant defence mechanisms, thereby improving plant tolerance to salinity. Simultaneously, organic amendments such as FYM and VC improve soil physical properties, moisture retention, microbial activity, and the gradual release of nutrients. These inputs also help buffer soil pH, reduce sodium buildup, and contribute to long-term soil fertility (Zalte et al. 2024). Observed that spinach irrigated with saline water (up to 4 dS/m EC) exhibited a proportional reduction in growth and yield attributes. However, the magnitude of this reduction varied among genotypes, suggesting that moderately salt-tolerant cultivars could be cultivated under saline conditions with minor yield penalties when supported by optimized nutrient management.

The outcomes of this study will contribute to the development of evidence-based recommendations for spinach cultivation in saline-affected and water-scarce regions. These findings are expected to support broader efforts toward enhancing food and nutritional security in vulnerable agro-ecological zones. In this context, a field experiment was conducted to assess the impact of irrigation water with varying salinity levels, in conjunction with different combinations of organic and inorganic nutrient inputs, on the growth, yield, and quality attributes of the spinach cultivar 'Thar Hariparna'.

Materials and Methods

A field experiment was conducted during the Rabi season of 2019-20 to 2020-21 at the ICAR-Central Institute for Arid Horticulture, Bikaner, situated in an arid agro-climatic zone. The experimental site had sandy, alkaline soil with a pH of 8.3. Pre-experimental soil analysis indicated low fertility, with 0.13% organic carbon, 113 kg ha⁻¹ available nitrogen, 12.2 kg ha⁻¹ available phosphorus (medium), and 222 kg ha⁻¹ available potassium.

Experiment design

The experiment was laid out in a randomized block design (RBD) with three replications, comprising twelve treatment combinations aimed at evaluating the interaction of different irrigation water salinity levels (0.5, 2.0, and 4.0 dS/m EC) and integrated nutrient management practices. Treatments included combinations of recommended dose of fertilizers (RDF), organic amendments (farmyard manure and vermicompost), and micronutrient applications (ZnSO₄ foliar spray @ 0.5%). The treatments were as follows: Treatment (1): Control (4 dS/m EC water), Treatment (2): 4 dS/m EC + RDF + VC + ZnSO₄ foliar spray, Treatment (3): 4 dS/m EC + RDF + FYM + ZnSO₄ foliar spray, Treatment (4): 4 dS/m EC + RDF + FYM + VC + ZnSO₄ foliar spray, Treatment (5): 2 dS/m EC only, Treatment (6): 2 dS/m EC + RDF + VC + ZnSO₄ foliar spray, Treatment(7): 2 dS/m EC + RDF + FYM + ZnSO₄ foliar spray, Treatment (8): 2 dS/m EC + RDF + FYM + VC + ZnSO₄ foliar spray, Treatment (9): 0.5 dS/m EC only, T10

– 0.5 dS/m EC + RDF + VC + ZnSO₄ foliar spray, Treatment(11): 0.5 dS/m EC + RDF + FYM + ZnSO₄ foliar spray, and Treatment (12): 0.5EC (IW) + RDF + FYM (50%) + VC (50%) + Micronutrient (Foliar spray of ZnSO₄ @ 0.5% + Soil application of FeSO₄ @ 0.5%).

Cultivar

Spinach, cultivar 'Thar Hariparna', was used as the test crop. Seeds were sown manually using a hand plough at a spacing of 30 cm between rows and 5 cm between plants. The full dose of NPK (100:60:40 kg ha⁻¹) was applied as a basal treatment before sowing. Foliar application of ZnSO₄ was done as per treatment specifications, and all agronomic practices were followed according to regional recommendations. For data collection, five randomly selected plants (excluding borders) per plot were used to record growth (plant height, leaf number, leaf area), physiological (chlorophyll a & b, carotenoids), biochemical (TSS, ascorbic acid), and yield traits at 45 and 60 days after sowing. Leaf samples were pre-treated with 0.1 N HCl to remove dust and residues, followed by rinsing with distilled water. The collected data were statistically analyzed using ANOVA, and treatment means were compared using the least significant difference (LSD) test at a 5% level of significance.

Results and Discussion

1. Vegetative Parameters

1.1 Plant height (cm)

The vegetative parameters plant height (cm), number of leaves per plant, leaf area per plant, and dry matter percentage presented in Table 1, exhibited significant variations under different salinity and nutrient management treatments. At 45 days after sowing (DAS), integrated nutrient management (INM) strategies had a pronounced effect on spinach growth. The control treatment (T1), irrigated with 4.0 dS/m EC saline water without any nutrient input, recorded the lowest plant height (17.48 cm). In contrast, the tallest plants (29.13 cm) were observed in Treatment T12 (0.5 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO₄ foliar spray @ 0.5% + FeSO₄ soil application @ 0.5%). Notably, even under high salinity (4.0 dS/m EC), Treatment T4 with the same nutrient inputs attained 28.59 cm height, indicating the salinity-ameliorating potential of INM (Table 1). These improvements are attributed to enhanced nutrient uptake, organic matter enrichment, and increased microbial activity due to FYM and vermicompost application. By avoiding the saline root environment, foliar-applied micronutrients are readily absorbed through leaf tissues, where they stimulate key enzymatic processes and support cell expansion. These findings are consistent with those of Bana et al. (2016), Zalte et al. (2023), who reported that organic amendments significantly enhance microbial activity and nutrient cycling in saline soils. Kandil et al. (2009) also emphasized the role of organic manures in improving soil structure, aeration, and water retention, thereby supporting better root development. Similarly, Sharma et al. (2014) demonstrated that the combined application of organic sources and micronutrients significantly improved spinach growth under abiotic stress. Earlier foundational studies by Atiyeh et al.

(2002) and Canellas et al. (2000) further validated that INM enhances vegetative growth and plant tolerance to salinity through improved soil fertility, microbial biomass, and physiological resilience.

1.2 Number of leaves/ plant

A similar trend was observed for the number of leaves per plant. The control recorded the lowest leaf count (9.0), while Treatment 12 (0.5 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO₄ foliar spray @ 0.5% + FeSO₄ soil application @ 0.5%). Notably, even under high salinity (4.0 dS/m EC) produced the highest number of leaves (15.8), followed closely by T11 (15.7) and T6 (15.6), (Table 1) all of which included either FYM or VC along with micronutrients. The increased leaf number in these treatments reflects the improved nutrient uptake and physiological stress conferred by integrated nutrient supply. A higher number of leaves translates into increased photosynthetic area and greater assimilate production, which are critical for overall biomass accumulation. These findings are consistent with previous reports on the beneficial effects of INM on leaf development in leafy vegetables. Moreover, the positive response in leaf number after successive cuttings may be attributed to continuous nutrient availability and hormonal regulation throughout the crop growth cycle, as also observed by Jha et al. (2009) and Zalte et al. (2023) in palak. The slight decline in leaf number in the third cutting could be due to increased leaf area and canopy competition (Table 1).

1.3 Leaf area (cm²)

Leaf area per plant, a vital indicator of photosynthetic capacity and overall plant vigor, showed significant variation across treatments. At 45 days after sowing (DAS), the highest leaf area was observed in T12 (0.5 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO₄ foliar spray @ 0.5% + FeSO₄ soil application @ 0.5%), recording 11.45 cm², followed by T11 (9.70 cm²) and T4 (9.42 cm²), whereas the lowest was in the control (T1), with only 3.36 cm². By 60 DAS, T10 (22.07 cm²) and T12 (16.76 cm²) (Table 1) continued to perform better,

while T1 remained the lowest (4.53 cm²). The increased leaf area observed under integrated nutrient management (INM) can be attributed to enhanced nitrogen uptake, improved chlorophyll synthesis, elevated protein production, and the regulation of phytohormones that stimulate cell division and expansion. These findings are consistent with the reports of Norman et al. (2005), Sharma (2014), and Zalte et al. (2023), which collectively highlight the beneficial role of INM in promoting vegetative growth and productivity in spinach cultivation.

1.4 Dry matter percentage

Dry matter (%) accumulation, a critical parameter reflecting biomass productivity and resource-use efficiency, was significantly influenced by integrated nutrient management (INM) practices. At 45 days after sowing (DAS), the highest dry matter content was recorded in Treatment T12 (0.5 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO₄ foliar spray @ 0.5% + FeSO₄ soil application @ 0.5%), reaching 6.57%, followed closely by T4 (6.46%) and T10 (6.39%) (Table 1). In contrast, the control treatment (T1), which was irrigated with saline water of 4.0 dS/m EC without any nutrient supplementation, recorded the lowest dry matter content (4.30%). At 60 days after sowing (DAS), both T12 and T4 treatments exhibited the highest dry matter accumulation (6.89%), whereas T1 continued to show the minimum value (5.75%). These statistically significant improvements can be attributed to enhanced nutrient availability, improved photosynthetic efficiency, and greater physiological resilience conferred by the integrated nutrient management (INM) strategies. The positive effects of INM under saline conditions are in agreement with findings by Atiyeh et al. (2002), Jha et al. (2009), and Norman et al. (2005), who emphasized the role of organic amendments and balanced nutrient inputs in enhancing plant physiological performance and tolerance to abiotic stress, particularly salinity.

Table 1. Effect of integrated application of organic and inorganic fertilizers with foliar and soil-applied micronutrients on growth attributes of spinach (*Beta vulgaris*) at 45 and 60 DAS under various salinity levels of irrigation water

Treatments	Plant height (cm)		Number of leaves per plant		Leaf area (cm ²) per plant		DM %	
	First cutting at 45 DAS	Second cutting at 60 DAS	First cutting at 45 DAS	Second cutting at 60 DAS	First cutting at 45 DAS	Second cutting at 60 DAS	First cutting at 45 DAS	Second cutting at 60 DAS
T1	17.48	17.60	9.0	15.6	3.36	4.53	4.3	5.75
T2	25.33	30.50	11.7	19.0	5.70	13.13	6.18	6.66
T3	21.30	25.57	10.7	20.3	4.84	10.90	6.33	6.73
T4	28.59	30.50	13.0	32.3	9.42	14.92	6.46	6.89
T5	21.11	32.93	12.3	32.3	4.42	17.32	4.77	5.54
T6	28.02	32.50	15.6	32.0	8.21	17.32	6.25	6.37
T7	24.62	26.42	12.0	31.3	7.73	10.95	5.76	6.28
T8	32.82	33.90	12.3	29.7	6.41	12.41	4.63	6.67
T9	20.19	25.63	11.7	35.3	5.88	18.38	5.01	5.87
T10	27.41	30.33	12.3	37.0	6.74	22.07	6.39	6.65
T11	27.78	35.67	15.7	34.3	9.70	16.29	6.12	6.75
T12	29.13	37.13	15.8	37.7	11.45	16.76	6.57	6.89
SEm±	1.23	0.89	0.8	1.3	0.64	1.37	1.08	1.143
CD @ 5%	4.57	5.61	2.3	3.8	1.88	4.01	0.86	1.02

2 Yield Parameters

2.1 Root length (cm)

Root development in spinach exhibited significant sensitivity to integrated nutrient management (INM) strategies under varying levels of irrigation water salinity. At 45 and 60 days after sowing (DAS), root length differed markedly among treatments. The shortest roots were recorded in the control (T1), which received high-salinity water (4.0 dS/m EC) without nutrient amendments, measuring 5.68 cm at 45 DAS and 8.50 cm at 60 DAS. In contrast, the greatest root elongation was observed in Treatment T11 (0.5 dS/m EC irrigation + RDF + 100% FYM + soil application of FeSO_4 @ 0.5%), achieving root lengths of 13.86 cm and 14.73 cm, respectively. This was followed by T6 (2.0 dS/m EC + RDF + 100% VC + FeSO_4 soil application) and T4 (4.0 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO_4 foliar spray @ 0.5% + FeSO_4 soil application @ 0.5%), both of which also showed substantial improvement in root development (Table 2). These findings underscore the synergistic effect of organic amendments, balanced nutrient supply, and micronutrient applications in mitigating salinity-induced stress. The improved root length is likely attributed to enhanced soil structure and porosity resulting from the application of FYM and vermicompost (VC), increased microbial biomass, and improved nutrient availability, all of which collectively reduce ionic toxicity and promote root elongation. These results are in agreement with the observations of Norman et al. (2005), Sharma et al. (2014), and Bhatti et al. (2004), who reported that the integrated use of organic amendments and micronutrients enhances root architecture and function under abiotic stress conditions.

2.2 Root Diameter (cm)

Root diameter was significantly influenced by integrated nutrient management (INM) under different salinity regimes. The minimum root thickness was observed in the control (T1), measuring 0.78 cm at 45 DAS and 0.97 cm at 60 DAS. In contrast, the highest root diameters were recorded in T6 (1.40 cm and 1.43 cm) and T12 (0.5 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO_4 foliar spray @ 0.5% + FeSO_4 soil application @ 0.5%), with 1.36 cm at 45 DAS and 1.43 cm at 60 DAS

(Table 2). These statistically significant increases (up to 0.26 cm) suggest improved nutrient reserves and structural integrity, attributed to a biologically active rhizosphere enriched with organic inputs and micronutrients, confirmed by Canellas et al. 2000 and Sharma et al. 2014. Total soluble solids (TSS), a key quality parameter, also responded positively to INM. T12 recorded the highest TSS (4.82% at 45 DAS, 6.77% at 60 DAS), followed by T7 and T10. The lowest was in T1 (2.77%), indicating impaired carbohydrate metabolism under salinity and nutrient stress. The enhancement in TSS is likely due to improved photosynthesis and assimilate accumulation under balanced nutrition and foliar micronutrient application (Sharma & Sharma 2014).

2.3 Yield (kg/ha)

Spinach yield was significantly influenced by integrated nutrient management (INM) under different salinity levels of irrigation. The control (T1), receiving only saline water (4.0 dS/m EC) without nutrient input, recorded the lowest yield (55.4 kg/ha at 45 DAS and 61.4 kg/ha at 60 DAS). In contrast, the highest total yield (266.8 kg/ha) was obtained in T12 (0.5 dS/m EC irrigation water + RDF + 50% FYM + 50% VC + ZnSO_4 foliar spray @ 0.5% + FeSO_4 soil application @ 0.5%). This was closely followed by T8 (260.7 kg/ha) and T4 (259.3 kg/ha), both under higher salinity levels but supported with balanced organic and micronutrient inputs (Figure 1). The enhanced yield is attributed to improved nutrient uptake, better root development, and reduced salinity stress due to synergistic effects of organic amendments and micronutrients. Treatments like T6, T10, and T11 also performed well, reaffirming the importance of combining FYM, VC, and micronutrients. These findings align with earlier reports by Bana et al. 2016; Norman et al. 2005; Mohammad et al. 2013; Jeevajothi et al. 1993) that highlight the role of INM in improving crop productivity under saline conditions. Overall, the study reaffirms that INM strategies incorporating both organic manures (such as FYM) and micronutrients through dual application routes are vital for sustaining high productivity and alleviating salt stress in arid agro-ecosystems.

Table 2. Effect of integrated application of organic and inorganic fertilizers with foliar and soil-applied micronutrients on yield attributes of spinach at 45 and 60 DAS under various salinity levels of irrigation water

Treatments	Root length (cm)		No. of roots/plant		Root diameter (cm)		TSS (%)	
	First cutting at 45 DAS	Second cutting at 60 DAS	First cutting at 45 DAS	Second cutting at 60 DAS	First cutting at 45 DAS	Second cutting at 60 DAS	First cutting at 45 DAS	Second cutting at 60 DAS
T1	5.68	8.50	3.69	5.67	0.78	0.97	3.76	2.77
T2	10.71	11.73	8.12	10.67	1.14	1.23	4.51	3.80
T3	9.64	10.63	7.18	8.67	1.07	1.22	4.35	4.23
T4	12.20	13.33	10.32	10.67	1.32	1.40	4.89	4.33
T5	9.21	11.60	6.80	10.00	1.04	1.10	4.29	5.17
T6	12.32	13.47	10.97	13.33	1.40	1.43	4.06	4.80
T7	11.98	12.30	9.24	12.67	1.22	1.53	4.70	5.87
T8	10.71	12.77	8.45	9.67	1.18	1.10	4.51	5.47
T9	10.86	13.47	8.26	11.67	1.15	1.10	4.54	5.43
T10	11.27	13.83	8.62	12.33	1.18	1.57	4.60	5.77

T11	13.86	14.73	10.57	12.67	1.34	1.37	4.99	5.80
T12	12.74	12.60	10.92	11.00	1.36	1.43	4.82	6.77
SEm±	0.85	0.71	0.52	1.09	0.05	0.09	0.13	0.13
CD (P=0.05)	2.49	2.10	1.53	3.19	0.14	0.26	0.37	0.39

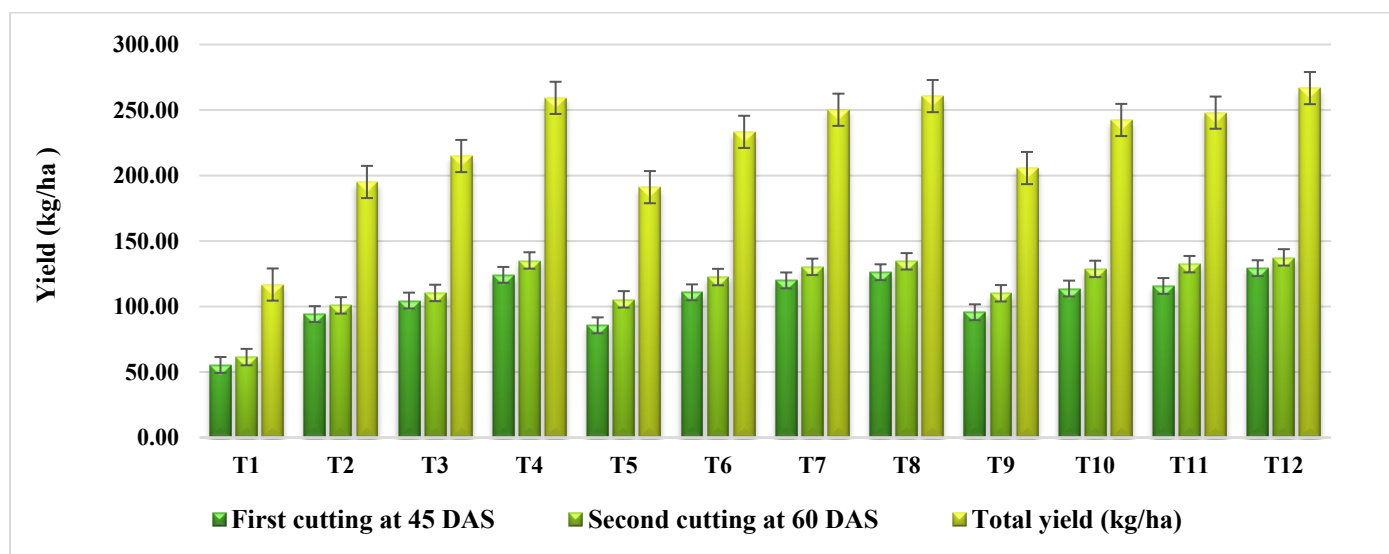


Figure 1. Effect of integrated application of organic and inorganic fertilizers with foliar and soil-applied micronutrients on yield of spinach at 45 and 60 DAS under various salinity levels of irrigation water

3 Effect of Integrated Application of Organic and Inorganic Fertilizers with Micronutrients on Photosynthetic Pigments and Ascorbic Acid in Spinach under Saline Irrigation

The biochemical analysis of spinach (*Beta vulgaris* L.) under varying salinity levels and nutrient management strategies revealed significant improvements in photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids) and ascorbic acid content due to integrated nutrient management (INM).

3.1 Chlorophyll a, b and Carotenoid content (mg/g fresh leaf weight)

Chlorophyll a and b concentrations were higher in the treatment receiving low-salinity irrigation water (0.5 dS/m EC) combined with the recommended dose of fertilizers (RDF), farmyard manure (FYM, 50%), vermicompost (50%), and micronutrient supplementation (ZnSO_4 foliar spray and FeSO_4 soil application). At 45 and 60 days after sowing (DAS), chlorophyll a levels reached 0.375 and 0.622 mg/g, while chlorophyll b levels measured 0.119 and 0.254 mg/g, respectively (Figure 2). These results indicate enhanced chlorophyll biosynthesis, likely driven by the improved availability of essential micronutrients such as iron and zinc. A similar trend was observed for carotenoid content, with the same treatment recording the highest values (0.432 and 0.515 mg/g at 45 and 60 DAS, respectively), reflecting a strengthened antioxidative

defense system under saline stress conditions. These findings are consistent with earlier studies by Maji et al. (2018), Padmanabha et al. (2008), and Gopinathan et al. (2014), which highlighted the positive impact of organic amendments and micronutrient supplementation on pigment accumulation and stress resilience in plants.

3.2 Ascorbic acid (mg/ 100g leaf weight)

Ascorbic acid (vitamin C) content exhibited a similar trend to that of chlorophyll and carotenoids, with the highest concentrations recorded in the most integrated treatment, combining 0.5 dS/m EC irrigation water with RDF, 50% FYM, 50% vermicompost, and micronutrient supplementation. At 45 and 60 days after sowing (DAS), ascorbic acid levels peaked at 29.97 and 29.89 mg/100g, respectively, while the control treatment (irrigated with 4.0 dS/m EC saline water without nutrient inputs) showed the lowest values, 18.27 and 17.37 mg/100g (Figure 2). The increase in ascorbic acid content under INM may be attributed to enhanced physiological activity, improved nutrient uptake, and stimulation of growth-regulating compounds, which collectively promote carbohydrate metabolism and antioxidant synthesis (Bharad et al., 2013). Overall, these results confirm that integrated nutrient management is effective in alleviating salinity-induced stress, enhancing pigment biosynthesis, and improving the nutritional quality of spinach.

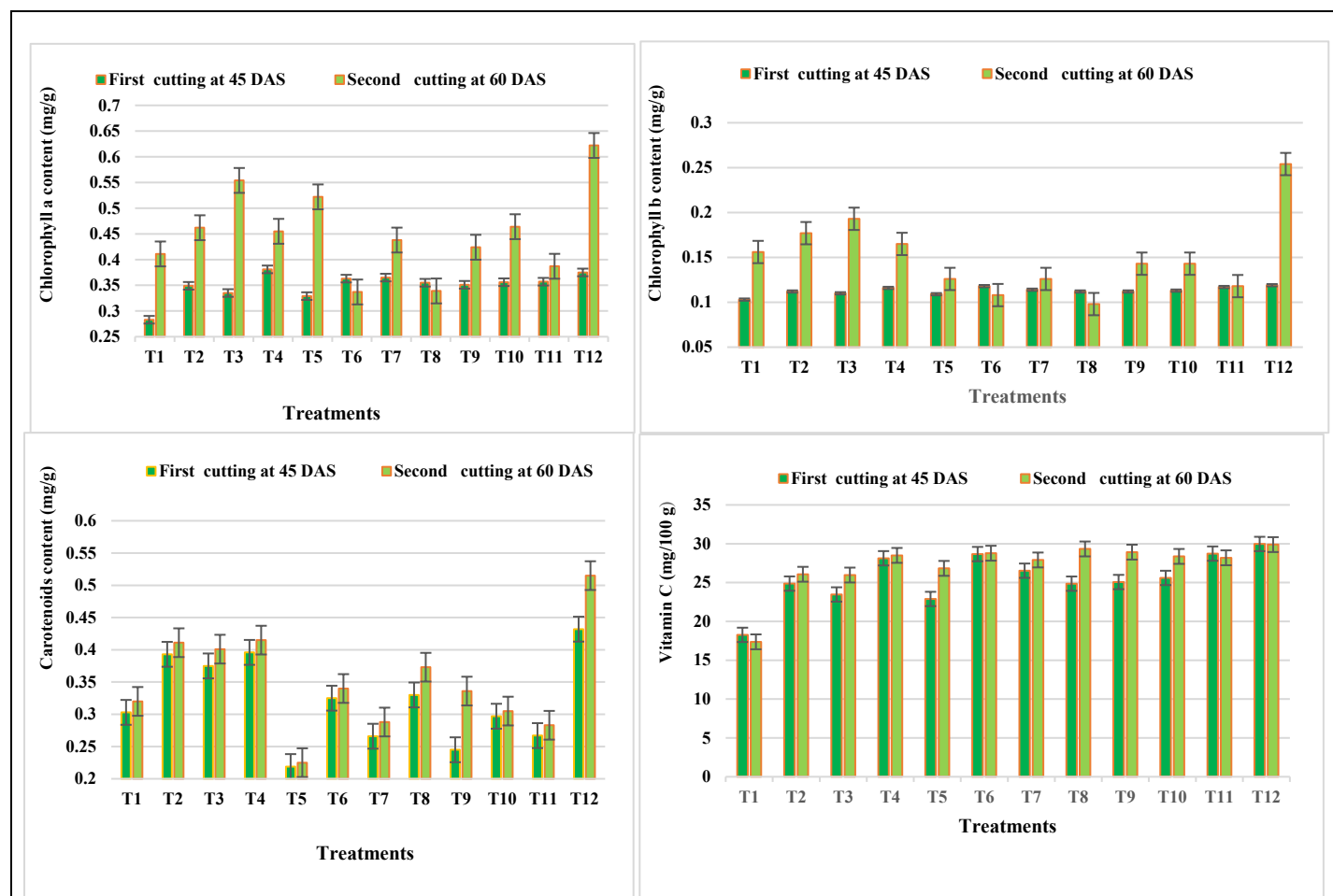


Figure 2. Effect of integrated application of organic and inorganic fertilizers with foliar and soil-applied micronutrients on Chlorophyll a content (mg/g), Chlorophyll b content (mg/g) carotenoids content (mg/g) and Vit C (mg/ 100g) under various salinity levels of irrigation water on Spinach cv Thar Hariparna; Error bars indicate critical difference at 5% level of significance; data is pooled of two years

Conclusion

The study demonstrates that optimizing integrated nutrient management (INM) through the combined use of FYM, vermicompost, RDF, and micronutrients via soil and foliar application significantly enhances spinach growth, yield, and quality under saline irrigation. The best results were observed in the treatment combining 0.5 dS/m EC irrigation with RDF + FYM (50%) + VC (50%) + Zn and Fe micronutrients, followed by T4, which also showed high performance under 4.0 dS/m EC. These treatments improved plant height, root traits, leaf area, dry matter, and yield (up to 259.3 kg/ha), even under salt stress. This highlights the effectiveness of INM in promoting sustainable spinach cultivation in saline and arid agro-ecosystems.

Declaration of interests

The authors do not have any conflict of interest, and the research was conducted in the absence of any commercial relationship with anyone.

Data Sharing

All relevant data are within the manuscript and are available from the first author.

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