



RESEARCH ARTICLE

Biofortification of brinjal with zinc and iron through fortified organics optimized NPK and bioactive compounds and their effects on the growth yield and quality of brinjal and on soil properties in coastal saline soil

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Abstract

Eggplant (aubergine or brinjal) is an important vegetable crop grown worldwide which is valued for its richness in dietary fibre and essential minerals such as calcium, iron, phosphorus and potassium. Brinjal is considered a heavy feeder of nutrients due to its long duration and high yield potential. In coastal nutrient-deficient soils, it is often cultivated without adequate nutrient management practices. To address this challenge, field experiments were conducted in a Randomized Block Design (RBD) with three replications. The trials were carried out during the kharif (2022–2023) and rabi (2022–2023) seasons in Ayikuppam village, Cuddalore district, Tamil Nadu. The study aimed to evaluate the effects of zinc and iron biofortification through fortified organics, optimised NPK and bioactive compounds on the growth, yield and quality of brinjal, as well as on soil properties in coastal saline soil. In both seasons, biofortification of brinjal with optimised dose of 150 % NPK + Zn and Fe fortified CCP at 6.25 t ha⁻¹ + 50 % ZnSO₄ and FeSO₄ at 12.5 kg ha⁻¹ along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 % + Naphthalene acetic acid (NAA) at 50 ppm + humic acid (HA) and sea weed extract (SWE) at 0.2 % at vegetative stage (VS) and flowering stages (FS) resulted in significantly higher mean plant height (121.97 cm), number of branches (40.24) number of fruits plant⁻¹ (35.97), single fruit weight (56.49 g), fruit length (31.77 cm), fruit (32.95 t ha⁻¹) and stover yield (47.88 t ha⁻¹) compared to control. This treatment also improved the quality of brinjal and soil properties of coastal land.

Keywords: fruit yield; humic acid; naphthalene acetic acid; stover yield

Introduction

Brinjal (*Solanum melongena* L.) is a widely cultivated vegetable crop famous for its culinary versatility and nutritional value in coastal regions. However, in many regions, suboptimal soil conditions and nutrient deficiencies challenge brinjal production, leading to reduced yield and nutritional quality. Addressing these challenges requires innovative agricultural practices that not only boost yield but also enhance the nutrient content of brinjal, thereby improving its overall nutritional value.

Biofortification, the process of increasing the concentration of essential nutrients in food crops through agronomic practices or breeding, has emerged as a promising strategy to combat malnutrition and improve public health (1). Zinc (Zn) and iron (Fe) are micronutrients critical for human health, playing an essential role in metabolic processes and immune system. Micronutrient deficiencies are common, especially in developing regions where monotonous diets restrict nutrient intake.

In recent years, biofortification efforts have expanded to include brinjal, with researchers exploring various approaches to increase Zn and Fe content in the fruit. These approaches include soil amendments with fortified organics and optimised NPK fertilization as well as incorporation of bioactive compounds such as seaweed extracts and humic acids. By synergistically enhancing nutrient availability, uptake and utilisation, these biofortification strategies hold the potential to significantly improve the growth, yield, quality and nutritional profile of brinjal (2).

This article aims to review and analyse the effect of biofortification techniques on brinjal production, focusing on their impact on plant growth, yield parameters, fruit quality attributes and soil properties. By investigating the mechanisms underlying these effects and evaluating the efficacy of different biofortification approaches, this study seeks to provide valuable insights for optimising brinjal cultivation practices and enhancing its nutritional value.

Materials and Methods

Field experiments were conducted during kharif and rabi season of 2022–2023 at same experiment site (Farmers field) in Ayikuppam village, Cuddalore district, Tamil Nadu.

Healthy Annamalai brinjal seeds were collected from the Department of Horticulture, Annamalai University, Chidambaram. The seeds were sown in seed trays and maintained under proper nursery management practices. After 27 days, the healthy and uniform brinjal seedlings were separated for transplanting. The main field was ploughed thoroughly and raised beds were prepared. The treatment plots were laid out with a size of 5 m × 4 m (20 m²), with adequate irrigation channels and bunds to avoid nutrient and water movement between plots. The brinjal saplings were transplanted from the nursery to the main field at a spacing of 60 cm × 45 cm. All agronomic practices were followed as per the standard TNAU Crop Production Guide.

The experimental soil was classified as sandy loam, exhibiting an alkaline reaction (pH 8.30) and moderate salinity (EC 3.96 dS m⁻¹). The soil fertility status indicated low levels of available nitrogen (178.46 kg ha⁻¹), available phosphorus (9.20 kg ha⁻¹), DTPA-extractable zinc (0.79 mg kg⁻¹) and DTPA-extractable iron (1.51 mg kg⁻¹), while the available potassium content (234.1 kg ha⁻¹) was within the medium range.

Treatment details

The experiment comprises 11 treatments which was laid in randomized block design (RBD) and replicated thrice. The treatments consist of T₁- Control (100 % NPK alone), T₂- 100 % NPK + Farm Yard Manure (FYM) at 12.5 t ha⁻¹ (Farmer's practice), T₃- 150 % NPK + 100 % Zn + Fe fortified CCP at 6.25 t ha⁻¹ + (ZnSO₄ + FeSO₄) 50 % soil application (SA) + 0.5 % ZnSO₄ + FeSO₄ foliar application (FA) at Vegetative stage (VS) and flowering stage (FS), T₄- T₃+ *Azospirillum* soil application, T₅- T₃+ Humic acid (HA) at 0.2 % foliar spray at VSFS, T₆- T₃+ Naphthalene acetic acid (NAA) at 50 ppm foliar spray at VS and FS, T₇- T₃+ Sea Weed Extract (SWE) at 0.2 % foliar spray at VS and FS, T₈- T₃+ *Azospirillum* + HA, T₉-T₃+ *Azospirillum* + NAA, T₁₀- T₃+ *Azospirillum* + SWE, T₁₁- T₃+ *Azospirillum* + HA + NAA +SWE. Blanket fertilizer application of 100:150:100 kg of N: P₂O₅: K₂O per hectare was done in all experimental plots uniformly.

Fortification of organics

For this study, coir pith compost was used as source of organics. The fortified organic manure was prepared by mixing the required quantity of composted coir pith (CCP) with the calculated amounts of micronutrients, namely ZnSO₄ at 25 kg ha⁻¹ and FeSO₄ at 25 kg ha⁻¹, as specified in the treatment schedule. Bioactive compounds, including auxins, amino acids, humic acids and seaweed extract, were each added at 1 mL kg⁻¹ of organic manure according to the treatment plan. The mixture was thoroughly blended and water was sprayed to maintain approximately 65 % of the soil's water-holding capacity. It was plastered with mud and incubated for a period of one month, with a stirring on 30th and 45th day. After 60 days, the fortified organic manure was used for the pot and field experiment. The chemical composition of fortified coir pith compost is presented in the Table 1.

Fertilizer application

Half of the N and entire P₂O₅ and K₂O were applied as basal dose and the remaining half dose of N was applied in two splits at flowering and fruit formation stage. Required quantities of Zn and Fe fortified compost coir pith organics 6.25 t ha⁻¹ were incorporated as per the treatment schedule. Required quantities of 100 % ZnSO₄ and FeSO₄ were applied to soil as basal as per treatment schedule. As per the treatment plan, ZnSO₄ and FeSO₄ were applied as a foliar spray at a concentration of 0.5 % during both the flowering and fruit formation stages. The biofertilizer namely *Azospirillum* at 2 kg ha⁻¹ was incorporated in all the plots. Humic acid and seaweed extract (SWE) was sprayed twice at flowering and fruit formation stages. For both seasons Annamalai brinjal variety was used as a test crop.

Parameters recorded

Growth parameters viz., plant height (cm) and numbers of branches per plant were observed from randomly selected 5 plants at harvest. Yield parameters viz., number of fruits plant⁻¹, fruit length (cm) and single fruit weight (gm) were observed at each picking and average was calculated within the 5 selected plants. Total fruit yield (t ha⁻¹) and stover yield (t ha⁻¹) were obtained at every harvest and total yield was worked out. The quality parameters like ascorbic acid content, total soluble solids (TSS) and titrable acidity in the fruit samples were estimated using the standard procedure (3).

Statistical analysis

The data obtained from the experiments were statistically analysed as per the standard procedure (4). For significant results, the critical difference was worked at 5 % probability level. The principal component analysis biplot and scatter plot matrix was analyzed in Origin Pro software.

Results and Discussion

Growth and yield

Application of bio active compounds and Zn + Fe nutrition favourably increased the growth attributes of brinjal viz., plant height and number of branches plant⁻¹, yield parameters viz., number of fruits plant⁻¹, single fruit weight and fruit length, fruit and stover yield (Table 1–3). Among the different treatments, soil application of *Azospirillum* at 2.0 kg ha⁻¹ and optimized dose of 150 % NPK + Zn and Fe fortified CCP at 6.25 t ha⁻¹ + 50 % ZnSO₄ and FeSO₄ at 12.5 kg ha⁻¹ along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 % + NAA at 50 ppm + HA and SWE at 0.2 % at VS and FS (T₁₁) recorded significantly mean higher plant height (121.97 cm), number of branches (40.24), dry matter production (24.55 t ha⁻¹), number of fruits plant⁻¹ (35.97), single fruit weight (56.49 g), fruit length (31.77 cm), fruit yield (36.22 t ha⁻¹) and stover yield (47.88 t ha⁻¹) of brinjal. However, the treatment T₁₀-was on par with T₉, while T₈ was on par with T₇. The treatment T₁₁ recorded mean fruit and stover yield of 36.22 and 47.88 t ha⁻¹, respectively which represent 33.83 and 27.37 % increase over control (Table 2–4).

Table 1. Chemical composition of coir pith and fortified coir pith used in the study

Organic manure	Organic carbon (%)	Major nutrients (%)				Micronutrients (mg kg ⁻¹)					C:N ratio
		N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	
Composted coirpith	24.0	1.06	0.26	1.20	0.52	0.41	919	52	59	31	19.10
Zinc fortified composted coirpith (ZnFCCP)	24.2	1.26	0.28	1.22	0.57	0.45	930	57	61	33	23.10
Iron fortified composted coirpith (FeFCCP)	24.5	1.18	0.29	1.25	0.59	0.46	920	55	60	32	22.12

Table 2. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the growth parameters of brinjal

Treatments	Plant height (cm)			Number of branches plant ⁻¹			Dry matter production (t ha ⁻¹)		
	1 st season	2 nd season	mean	1 st season	2 nd season	mean	1 st season	2 nd season	mean
T ₁	91.28	111.56	101.42 ^g ± 1.08	24.53	29.98	27.25 ^g ± 0.67	16.2	21.92	19.06 ^g ± 0.27
T ₂	93.43	114.19	103.81 ^{fg} ± 1.08	25.87	31.61	28.74 ^{fg} ± 0.67	16.7	22.60	19.65 ^{fg} ± 0.27
T ₃	95.53	116.75	106.14 ^f ± 1.08	27.24	33.30	30.27 ^f ± 0.67	17.2	23.30	20.26 ^f ± 0.27
T ₄	97.75	119.47	108.61 ^e ± 1.08	28.66	35.02	31.84 ^e ± 0.67	17.8	24.02	20.89 ^e ± 0.27
T ₅	99.95	122.16	111.05 ^{de} ± 1.08	30.04	36.72	33.38 ^{de} ± 0.67	18.3	24.78	21.55 ^{de} ± 0.27
T ₆	102.12	124.82	113.47 ^{cd} ± 1.08	31.41	38.39	34.90 ^{cd} ± 0.67	18.9	25.58	22.24 ^{cd} ± 0.27
T ₇	104.33	127.51	115.92 ^{bc} ± 1.08	32.90	40.21	36.55 ^{bc} ± 0.67	19.4	26.29	22.86 ^{bc} ± 0.27
T ₈	104.91	128.23	116.57 ^{bc} ± 1.08	33.14	40.50	36.82 ^{bc} ± 0.67	19.6	26.55	23.09 ^{bc} ± 0.27
T ₉	107.08	130.88	118.98 ^{ab} ± 1.08	34.50	42.16	38.33 ^{ab} ± 0.67	20.2	27.29	23.73 ^{ab} ± 0.27
T ₁₀	107.45	131.33	119.39 ^{ab} ± 1.08	34.79	42.53	38.66 ^{ab} ± 0.67	20.3	27.45	23.87 ^{ab} ± 0.27
T ₁₁	109.77	134.17	121.97 ^a ± 1.08	36.22	44.26	40.24 ^a ± 0.67	20.9	28.23	24.55 ^a ± 0.27
SE _D	0.97	1.19		0.60	0.74		0.2	0.31	
CD (p=0.05)	2.03	2.48		1.27	1.55		0.5	0.64	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

Table 3. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the yield parameters of brinjal

Treatments	Number of fruits plant ⁻¹			Single fruit weight (g)			Fruit length (cm)		
	1 st season	2 nd season	mean	1 st season	2 nd season	mean	1 st season	2 nd season	mean
T ₁	25.78	34.37	28.64 ^e ± 0.39	39.15	52.2	43.50 ^f ± 0.67	22.47	29.96	24.97 ^f ± 0.35
T ₂	26.58	35.44	29.53 ^e ± 0.39	40.49	53.99	44.99 ^f ± 0.67	23.15	30.86	25.72 ^f ± 0.35
T ₃	27.4	36.53	30.44 ^{de} ± 0.39	41.87	55.82	46.52 ^e ± 0.67	23.86	31.81	26.51 ^e ± 0.35
T ₄	28.17	37.56	31.30 ^d ± 0.39	43.28	57.71	48.09 ^d ± 0.67	24.55	32.74	27.28 ^{de} ± 0.35
T ₅	28.94	38.58	32.15 ^c ± 0.39	44.67	59.56	49.63 ^c ± 0.67	25.22	33.62	28.02 ^{cd} ± 0.35
T ₆	29.72	39.62	33.02 ^c ± 0.39	46.04	61.38	51.15 ^c ± 0.67	25.95	34.6	28.83 ^c ± 0.35
T ₇	30.47	40.63	33.86 ^b ± 0.39	47.52	63.36	52.80 ^b ± 0.67	26.69	35.59	29.66 ^b ± 0.35
T ₈	30.68	40.91	34.09 ^b ± 0.39	47.76	63.68	53.07 ^b ± 0.67	26.83	35.77	29.81 ^b ± 0.35
T ₉	31.45	41.93	34.94 ^a ± 0.39	49.12	65.5	54.58 ^a ± 0.67	27.63	36.84	30.70 ^a ± 0.35
T ₁₀	31.55	42.07	35.06 ^a ± 0.39	49.42	65.89	54.91 ^a ± 0.67	27.83	37.1	30.92 ^a ± 0.35
T ₁₁	32.37	43.16	35.97 ^a ± 0.39	50.84	67.79	56.49 ^a ± 0.67	28.59	38.12	31.77 ^a ± 0.35
SE _D	0.35	0.47		0.6	0.8		0.32	0.42	
CD (p=0.05)	0.74	0.98		1.25	1.67		0.66	0.88	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

Table 4. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the yield of brinjal

Treatments	Fruit yield (t ha ⁻¹)			Stover yield (t ha ⁻¹)		
	1 st season	2 nd season	mean	1 st season	2 nd season	mean
T ₁	27.01	28.77	27.89 ^e ± 0.55	37.48	37.7	37.59 ^e ± 0.67
T ₂	28.07	29.55	28.81 ^e ± 0.55	38.2	39.36	38.78 ^e ± 0.67
T ₃	28.82	30.68	29.75 ^{de} ± 0.55	39.57	40.45	40.01 ^{de} ± 0.67
T ₄	30.51	31.01	30.76 ^d ± 0.55	40.43	41.89	41.16 ^d ± 0.67
T ₅	31.1	32.64	31.87 ^{cd} ± 0.55	41.44	43.16	42.30 ^{cd} ± 0.67
T ₆	32.17	33.81	32.99 ^c ± 0.55	43.41	43.63	43.52 ^c ± 0.67
T ₇	33.69	34.13	33.91 ^{bc} ± 0.55	44.33	45.21	44.77 ^{bc} ± 0.67
T ₈	33.53	34.45	33.99 ^b ± 0.55	44.84	45.28	45.06 ^b ± 0.67
T ₉	34.31	35.77	35.04 ^b ± 0.55	45.3	47.24	46.27 ^b ± 0.67
T ₁₀	35.04	35.48	35.26 ^{ab} ± 0.55	45.59	47.61	46.60 ^{ab} ± 0.67
T ₁₁	36.11	36.33	36.22 ^a ± 0.55	47.84	47.92	47.88 ^a ± 0.67
SE _D	0.43	0.46		0.54	0.57	
CD (p=0.05)	0.89	0.96		1.11	1.17	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

Incorporating *Azospirillum* bacteria enhances soil nutrient availability and root development, while synthetic auxin NAA promotes root growth, flowering and fruit development (4). Naphthalene acetic acid is especially beneficial in saline conditions, aiding fruit set and yield. Seaweed extract boosts plant health by facilitating nutrient uptake and enhancing resistance to environmental stresses like drought and salinity (5). It also helps with osmotic adjustment, crucial in saline soils to maintain water balance. Both HA SWE improve nutrient availability by chelating soil nutrients, aiding brinjal plant growth in saline soils. Optimized nutrient combinations like NPK, Zn and Fe-fortified CCP, along with soil-applied ZnSO₄ and FeSO₄, provide balanced nutrition. Foliar spray of ZnSO₄ and FeSO₄, NAA, HA and SWE during vegetative and flowering stages directly supplies essential nutrients and growth regulators, fostering healthy growth, flower initiation and fruit development, thus improving yield (6).

Quality characters

The data presented in Table 5 shows that among various treatments, the application of 150 % NPK + *Azospirillum* at 2 kg ha⁻¹ + Zn & Fe fortified CCP at 6.25 t ha⁻¹ + 50 % ZnSO₄ and FeSO₄ at 12.5 kg ha⁻¹ through soil (SA) along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 % + NAA at 50 ppm + HA and SWE at 0.2 % at VSFS (T₁₁) recorded the significant mean higher quality parameters of brinjal viz., ascorbic acid content (16.88 mg 100 g⁻¹ fruit), crude protein content (4.13 %), titrable acidity (2.14 %), total soluble solid (16.92 %), zinc content (24.78 %), iron content (5.84 %). This was followed by the treatment T₁₀, which was on par with T₉. Further the treatment T₈ on par with T₇. This was followed by the treatments arranged in descending order viz., T₆>T₅>T₄>T₃>T₂ and T₁ (Fig. 1).

Naphthalene acetic acid, a synthetic auxin, boosts plant metabolism, potentially elevating titrable acidity in brinjal fruit for a balanced flavour. When combined with SWE, it promotes the synthesis of organic compounds like ascorbic acid, enriching the fruit's antioxidant content. SWE aids osmotic regulation and stress relief, enhancing total soluble solids (TSS) in brinjal, improving sweetness. *Azospirillum* incorporation, alongside NAA, HA and SWE, influences plant metabolism, leading to balanced acidity, increased ascorbic acid, enhanced TSS and higher iron and zinc levels in brinjal. These practices, incorporated during vegetative and flowering stages, optimize nutrient uptake, fostering improved brinjal quality for both plant health and human nutrition (7–9). The scatter plot matrix and PCA biplot showed that all brinjal, quality parameters (ascorbic acid, crude protein, titrable acidity and total soluble solids) were positively interrelated, indicating simultaneous improvement with increasing Zn and Fe availability (Fig 2, 3)

Soil properties

Major nutrients

The available macronutrients show significant effect for the various treatments which is presented in Table 6. Among various treatments, T₁₁ recorded significantly higher alkaline KMnO₄-N, Olsen P and NH₄OAc-K content in soil (170.90 kg N ha⁻¹, 15.29 kg P ha⁻¹ and 218.57 kg K ha⁻¹) at harvest stage. The treatment T₁₀ was on par with T₉ and T₈ was on par with T₇ which recorded the comparable alkaline KMnO₄-N, Olsen P and NH₄OAc-K content of 163.77, 14.29 and 210.42 kg ha⁻¹, respectively at harvest stage. This was followed by the treatments arranged in descending order viz.,

Table 5. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the quality parameters of brinjal

Treatments	Ascorbic acid content (mg 100 g ⁻¹ fruit)			Crude protein content (%)			Titrable acidity (%)			Total soluble solid (%)			
	1 st season		2 nd season	1 st season		2 nd season	1 st season		2 nd season	1 st season		2 nd season	
	mean	SE	mean	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE
T ₁	9.51	0.35 ^k	10.01 ± 0.35 ^k	1.30	0.10 ^k	1.37 ± 0.10 ^k	0.31	0.07 ^k	0.33 ± 0.07 ^k	10.75	0.30 ^k	11.29	0.30 ^k
T ₂	10.28	0.35 ^j	10.82 ± 0.35 ^j	1.58	0.10 ^j	1.66 ± 0.10 ^j	0.49	0.07 ^j	0.52 ± 0.07 ^j	11.43	0.30 ^j	12.00	0.30 ^j
T ₃	11.07	0.35 ⁱ	11.65 ± 0.35 ⁱ	1.93	0.10 ⁱ	2.03 ± 0.10 ⁱ	0.70	0.07 ⁱ	0.74 ± 0.07 ⁱ	12.12	0.30 ⁱ	12.73	0.30 ⁱ
T ₄	11.88	0.35 ^h	12.51 ± 0.35 ^h	2.27	0.10 ^h	2.39 ± 0.10 ^h	0.95	0.07 ^h	1.00 ± 0.07 ^h	12.84	0.30 ^h	13.49	0.30 ^h
T ₅	12.64	0.35 ^g	13.30 ± 0.35 ^g	2.64	0.10 ^g	2.78 ± 0.10 ^g	1.23	0.07 ^g	1.29 ± 0.07 ^g	13.59	0.30 ^g	14.27	0.30 ^g
T ₆	13.51	0.35 ^f	14.22 ± 0.35 ^f	2.92	0.10 ^f	3.07 ± 0.10 ^f	1.41	0.07 ^f	1.48 ± 0.07 ^f	14.37	0.30 ^f	15.09	0.30 ^f
T ₇	14.31	0.35 ^e	15.06 ± 0.35 ^e	3.21	0.10 ^e	3.38 ± 0.10 ^e	1.61	0.07 ^e	1.69 ± 0.07 ^e	15.17	0.30 ^e	15.93	0.30 ^e
T ₈	14.41	0.35 ^d	15.17 ± 0.35 ^d	3.28	0.10 ^d	3.45 ± 0.10 ^d	1.62	0.07 ^d	1.71 ± 0.07 ^d	15.35	0.30 ^d	16.12	0.30 ^d
T ₉	15.24	0.35 ^c	16.04 ± 0.35 ^c	3.58	0.10 ^c	3.77 ± 0.10 ^c	1.83	0.07 ^c	1.93 ± 0.07 ^c	16.08	0.30 ^c	16.89	0.30 ^c
T ₁₀	15.29	0.35 ^b	16.09 ± 0.35 ^b	3.61	0.10 ^b	3.80 ± 0.10 ^b	1.86	0.07 ^b	1.96 ± 0.07 ^b	16.21	0.30 ^b	17.02	0.30 ^b
T ₁₁	16.13	0.35 ^a	16.98 ± 0.35 ^a	3.95	0.10 ^a	4.16 ± 0.10 ^a	2.14	0.07 ^a	2.25 ± 0.07 ^a	16.96	0.30 ^a	17.81	0.30 ^a
SE _D	0.33		0.35	0.10		0.10	0.07		0.07		0.29	0.30	
CD (p=0.05)	0.70		0.74	0.20		0.21	0.13		0.14		0.60	0.63	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

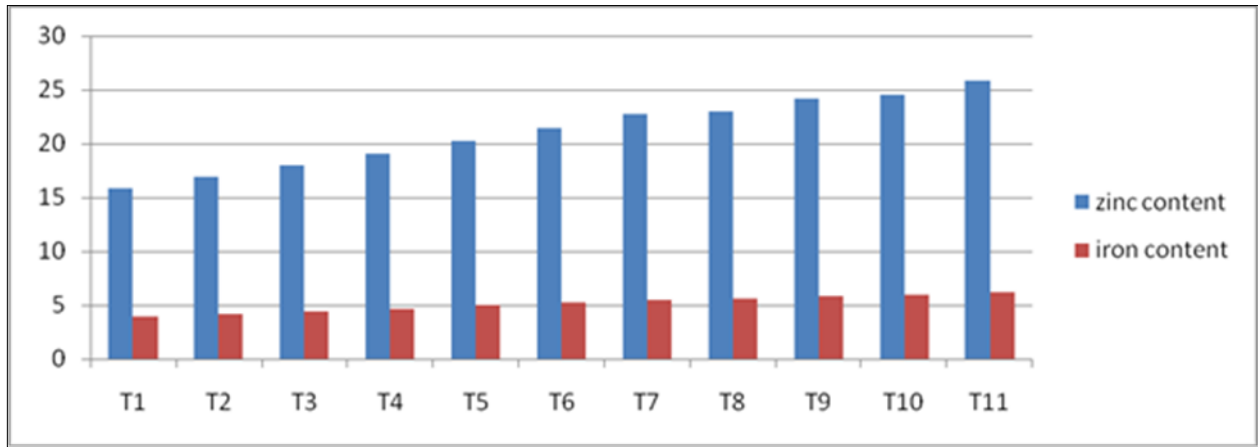


Fig. 1. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the zinc and iron content (%) of brinjal.

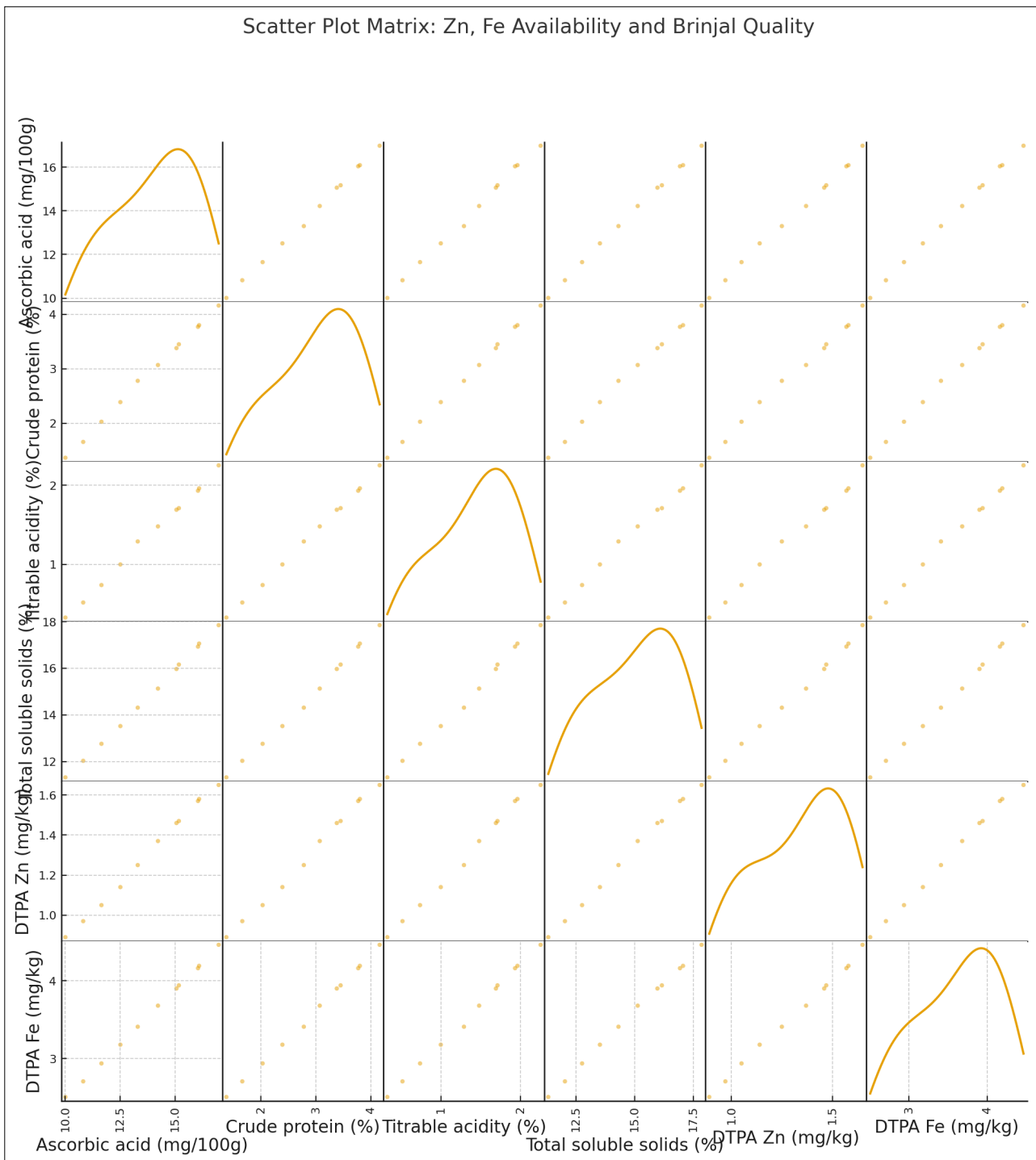


Fig. 2. Scatter plot matrix analysis for Zn and Fe availability in soil with quality parameters.

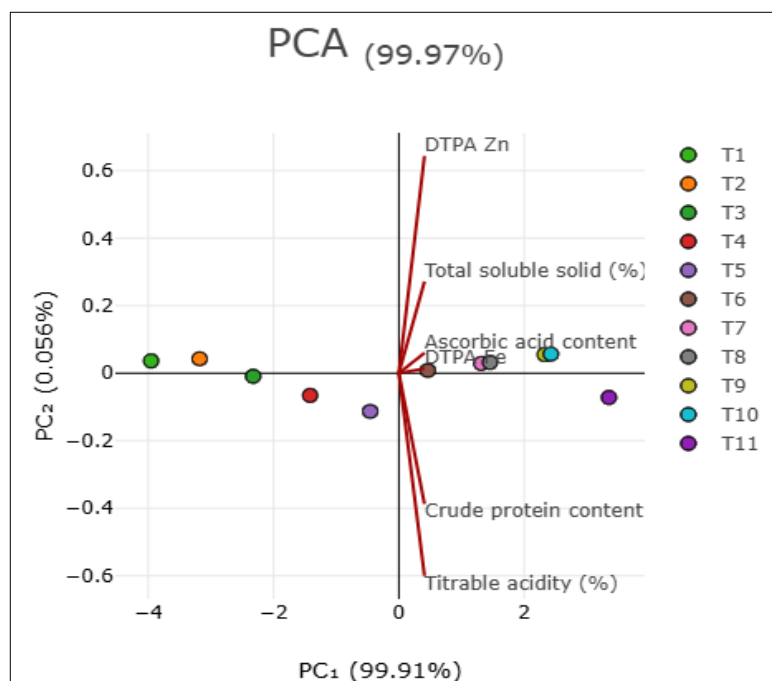


Fig. 3. Principal component analysis biplot analysis for Zn and Fe availability in soil with quality parameters.

$T_6 > T_5 > T_4 > T_3 > T_2$ and T_1 . An increase in available NPK in the soil might be due to the synergistic effect between zinc and iron. The zinc and iron enriched treatments showed increased NPK content of the soil, which was attributed to the different levels of fertilizer zinc and iron. Further, foliar application of zinc and iron in the form of zinc sulphate and iron sulphate enhances nutrient availability because these elements rapidly participate in passive adsorption mechanisms, allowing quick exchange with P and K and reducing their fixation, thereby improving overall nutrient availability in the soil (10–13).

Micro nutrients

The significant variation of the data in Table 7 indicated that among the various treatment, T_{11} - Soil application of *Azospirillum* at 1.5 kg ha^{-1} and optimized dose of 150 % NPK + Zn and Fe fortified CCP at 6.25 t ha^{-1} + $ZnSO_4$ and $FeSO_4$ at 3.75 kg ha^{-1} along with foliar spray of $ZnSO_4$ & $FeSO_4$ at 0.5 % + Naphthalene acetic acid (NAA) at 50 ppm + HA and SWE at 0.2 % at VSFS recorded the higher available mean DTPA Zn and DTPA Fe content of 1.65 and 4.46 mg kg^{-1} at HS. This was followed by the treatment T_{10} , Soil application of *Azospirillum* at 1.5 kg ha^{-1} and optimised dose of 150 % NPK + Zn and Fe fortified

CCP at 6.25 t ha^{-1} + $ZnSO_4$ and $FeSO_4$ at 3.75 kg ha^{-1} along with foliar spray of $ZnSO_4$ & $FeSO_4$ at 0.5 % and sea weed extract (SWE) at 0.2 % at VS and FS and recorded the DTPA Zn and Fe content of 1.58 and 4.19 mg kg^{-1} at HS. However the treatment T_{10} was on par with T_9 (Soil application of *Azospirillum* at 1.5 kg ha^{-1} and optimised dose of 150 % NPK + Zn and Fe fortified CCP at 6.25 t ha^{-1} + $ZnSO_4$ and $FeSO_4$ at 3.75 kg ha^{-1} along with foliar spray of $ZnSO_4$ & $FeSO_4$ at 0.5 % and NAA at 50ppm at VS and FS). This was followed by the treatment which are arranged in descending order like $T_8 > T_7 > T_6 > T_5 > T_4 > T_3$ and T_2 . In this order the treatment T_8 and T_7 was on par with each other. The lowest available Zn and Fe content was noted in control - T_1 . The soil and foliar application of $ZnSO_4$ and $FeSO_4$ along with recommended chemical fertilizer and enriched organics may increases the utilisation of nutrients mainly due to its beneficial effect in mobilising the native nutrients to increase their uptake and ultimately leads to lower availability in soil after the harvest (14, 15). The scatter plot matrix and PCA biplot revealed a strong positive association between soil Zn and Fe availability and all quality parameters of brinjal, indicating that higher micronutrient availability consistently enhanced fruit quality traits (Fig. 3).

Table 6. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the major nutrients availability in soil

Treatments	Alkaline $KMnO_4$ -N (kg ha^{-1})			Olsen-P (kg ha^{-1})			NH_4OAc -K (kg ha^{-1})		
	1 st	2 nd	mean	1 st	2 nd	mean	1 st	2 nd	mean
	season	season		season	season		season	season	
T_1	155.64	139.96	147.80 ± 1.11 ^k	12.41	11.22	11.82 ± 0.17 ^k	216.85	166.98	191.92 ± 1.28 ^k
T_2	158.53	142.25	150.39 ± 1.11 ^j	12.83	11.55	12.19 ± 0.17 ^j	220.14	169.73	194.94 ± 1.28 ^j
T_3	161.45	144.59	153.02 ± 1.11 ⁱ	13.27	11.91	12.59 ± 0.17 ⁱ	223.45	172.50	197.98 ± 1.28 ⁱ
T_4	164.41	146.95	155.68 ± 1.11 ^h	13.73	12.30	13.02 ± 0.17 ^h	226.78	175.32	201.05 ± 1.28 ^h
T_5	167.39	149.34	158.37 ± 1.11 ^g	14.21	12.62	13.42 ± 0.17 ^g	230.14	178.16	204.15 ± 1.28 ^g
T_6	170.44	151.75	161.10 ± 1.11 ^f	14.71	12.96	13.84 ± 0.17 ^f	233.53	181.02	207.28 ± 1.28 ^f
T_7	173.33	154.20	163.77 ± 1.11 ^e	15.23	13.34	14.29 ± 0.17 ^e	236.93	183.90	210.42 ± 1.28 ^e
T_8	174.45	155.07	164.76 ± 1.11 ^d	15.32	13.45	14.39 ± 0.17 ^d	237.94	184.85	211.40 ± 1.28 ^d
T_9	177.44	157.42	167.43 ± 1.11 ^c	15.77	13.80	14.79 ± 0.17 ^c	241.29	187.62	214.46 ± 1.28 ^c
T_{10}	178.51	157.86	168.19 ± 1.11 ^b	15.88	13.87	14.88 ± 0.17 ^b	242.38	188.65	215.52 ± 1.28 ^b
T_{11}	181.54	160.25	170.90 ± 1.11 ^a	16.35	14.22	15.29 ± 0.17 ^a	245.77	191.37	218.57 ± 1.28 ^a
SE _D	1.36	1.08		0.18	0.15		1.56	1.26	
CD ($p=0.05$)	2.85	2.26		0.38	0.31		3.26	2.64	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

Table 7. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the zinc and iron availability in soil

Treatments	DTPA Zn (mg kg ⁻¹)			DTPA Fe (mg kg ⁻¹)		
	1 st season	2 nd season	mean	1 st season	2 nd season	mean
T ₁	1.05	0.73	0.89 ± 0.02 ^k	2.90	2.11	2.51 ± 0.05 ^k
T ₂	1.12	0.82	0.97 ± 0.02 ^j	3.09	2.33	2.71 ± 0.05 ^j
T ₃	1.21	0.89	1.05 ± 0.02 ⁱ	3.30	2.57	2.94 ± 0.05 ⁱ
T ₄	1.31	0.97	1.14 ± 0.02 ^h	3.52	2.83	3.18 ± 0.05 ^h
T ₅	1.42	1.07	1.25 ± 0.02 ^g	3.71	3.11	3.41 ± 0.05 ^g
T ₆	1.55	1.19	1.37 ± 0.02 ^f	3.94	3.41	3.68 ± 0.05 ^f
T ₇	1.64	1.27	1.46 ± 0.02 ^e	4.16	3.64	3.90 ± 0.05 ^e
T ₈	1.66	1.28	1.47 ± 0.02 ^d	4.21	3.66	3.94 ± 0.05 ^d
T ₉	1.77	1.37	1.57 ± 0.02 ^c	4.40	3.92	4.16 ± 0.05 ^c
T ₁₀	1.78	1.37	1.58 ± 0.02 ^b	4.44	3.93	4.19 ± 0.05 ^b
T ₁₁	1.85	1.44	1.65 ± 0.02 ^a	4.69	4.22	4.46 ± 0.05 ^a
SE _D	0.03	0.02		0.08	0.09	
CD (p=0.05)	0.06	0.05		0.16	0.19	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

Microbial population

The application of fortified CCP along with inorganic nutrients show significant variation on microbial populations in soil and the values are depicted in Table 8. Among the various treatments, the application of 150 % NPK + *Azospirillum* at 2 kg ha⁻¹ + Zn & Fe fortified CCP at 6.25 t ha⁻¹ + 50 % ZnSO₄ and FeSO₄ at 12.5 kg ha⁻¹ through soil (SA) along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 % + NAA at 50 ppm + HA and SWE at 0.2 % at VS and FS (T₁₁) recorded the significant mean higher microbial populations viz., bacteria (23.65 × 10⁶ g⁻¹ soil), fungi (14.65 × 10⁵ g⁻¹ soil) and Actinomycetes (9.79 × 10⁴ g⁻¹ soil). This was followed by the treatment T₁₀, which was on par with T₉. This was followed by the treatment T₈, which was on par with T₇. This was followed by the treatments arranged in descending order viz., T₆>T₅>T₄>T₃>T₂ and T₁. Increase in microbial population could be the result of enhancement of soil organic matter in the soil due to by positive correlation of enzyme activities with soil organic carbon. This can be ascribed to the decomposed food material available from organic sources. Similar results were reported by several researchers (16, 17) who reported that the microbial population was almost doubled with the balanced and integrated use of chemical fertilizers and organics than with imbalanced use of chemical fertilizers and treatments involving the use of 100 % NPK.

Enzymatic activities

The enzyme activities in the soil were depicted in Table 9 and it

shows that the Soil application of *Azospirillum* at 1.5 kg ha⁻¹ and optimised dose of 150 % NPK + Zn and Fe fortified CCP at 6.25 t ha⁻¹ + ZnSO₄ and FeSO₄ at 3.75 kg ha⁻¹ along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 % + NAA at 50 ppm + HA and SWE at 0.2 % at VSFS (T₁₁) significantly increased the enzymatic activities in soil (Table 7). This treatment recorded the highest enzymatic activities of urease (32.47 µg NH₄-N/g soil/24 hr), phosphatase (16.01 µg *p*-nitrophenol/g soil/hr) and dehydrogenase (76.34 µg TTF/g soil/24 hr) in soil at fruit formation stage. This was followed by the treatment T₁₀ which received soil application of *Azospirillum* at 1.5 kg ha⁻¹ and optimized dose of 150 % NPK + Zn and Fe fortified CCP at 6.25 t ha⁻¹ + ZnSO₄ and FeSO₄ at 3.75 kg ha⁻¹ along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 % and seaweed extract (SWE) at 0.2 % at VS and FS. However, the treatment T₁₀ was on par with T₉ and T₈ was on par with T₇. This was followed by the treatments arranged in descending order viz., T₆>T₅>T₄>T₃>T₂ and T₁. In general, the activity of the three enzymes studied was significantly higher in treatment T₁₁. This is attributed to sufficient supply of energy source i.e. carbon from the organics and readily available nutrients from inorganic fertilizers. Further, application of organic matter provides proper aeration, moisture content and nutrients which results in proliferation of microorganisms. The enhanced levels of soil enzymatic activity due to addition of organic manures along with mineral nutrients (3). Several researchers observed significantly improved dehydrogenase and phosphatase activity in soil which received

Table 8. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the microbial population in soil

Treatments	Bacteria (x 10 ⁶ /g soil)			Fungi (x 10 ⁵ /g soil)			Actinomycetes (x 10 ⁴ /g soil)		
	1 st season	2 nd season	mean	1 st season	2 nd season	mean	1 st season	2 nd season	mean
T ₁	20.87	23.48	22.18 ± 0.33 ^k	13.03	13.81	13.42 ± 0.04 ^k	8.03	8.96	8.50 ± 0.06 ^k
T ₂	21.01	23.63	22.32 ± 0.33 ^j	13.16	13.93	13.55 ± 0.04 ^j	8.17	9.10	8.64 ± 0.06 ^j
T ₃	21.17	23.80	22.49 ± 0.33 ⁱ	13.31	14.09	13.70 ± 0.04 ⁱ	8.34	9.26	8.80 ± 0.06 ⁱ
T ₄	21.35	23.99	22.67 ± 0.33 ^h	13.48	14.23	13.86 ± 0.04 ^h	8.53	9.44	8.99 ± 0.06 ^h
T ₅	21.54	24.20	22.87 ± 0.33 ^g	13.67	14.41	14.04 ± 0.04 ^g	8.67	9.57	9.12 ± 0.06 ^g
T ₆	21.75	24.37	23.06 ± 0.33 ^f	13.88	14.54	14.21 ± 0.04 ^f	8.83	9.72	9.28 ± 0.06 ^f
T ₇	21.97	24.55	23.26 ± 0.33 ^e	14.00	14.71	14.36 ± 0.04 ^e	8.95	9.89	9.42 ± 0.06 ^e
T ₈	22.01	24.59	23.30 ± 0.33 ^d	14.02	14.73	14.38 ± 0.04 ^d	8.96	9.92	9.44 ± 0.06 ^d
T ₉	22.14	24.76	23.45 ± 0.33 ^c	14.13	14.86	14.50 ± 0.04 ^c	9.15	10.05	9.60 ± 0.06 ^c
T ₁₀	22.16	24.81	23.49 ± 0.33 ^b	14.14	14.90	14.52 ± 0.04 ^b	9.19	10.07	9.63 ± 0.06 ^b
T ₁₁	22.33	24.97	23.65 ± 0.33 ^a	14.29	15.01	14.65 ± 0.04 ^a	9.36	10.22	9.79 ± 0.06 ^a
SE _D	0.06	0.07		0.04	0.05		0.05	0.06	
CD (p=0.05)	0.12	0.14		0.09	0.10		0.11	0.12	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

Table 9. Effect of biofortification of zinc and iron through fortified organics, optimized NPK and bioactive compounds on the enzymatic activities in soil

Treatments	Urease activity (mg NH ₄ -N/g soil/24 h)			Phosphatase activity (mg p-nitrophenol/g soil/hr)			Dehydrogenase activity (mg TTF/g soil/24 h)		
	1 st season	2 nd season	mean	1 st season	2 nd season	mean	1 st season	2 nd season	mean
T ₁	29.73	31.97	30.85 ± 0.29 ^k	14.01	14.81	14.41 ± 0.10 ^k	73.54	75.65	74.60 ± 0.08 ^k
T ₂	29.89	32.14	31.02 ± 0.29 ^j	14.16	14.98	14.57 ± 0.10 ^j	73.71	75.84	74.78 ± 0.08 ^j
T ₃	30.05	32.33	31.19 ± 0.29 ⁱ	14.33	15.17	14.75 ± 0.10 ⁱ	73.90	76.06	74.98 ± 0.08 ⁱ
T ₄	30.23	32.51	31.37 ± 0.29 ^h	14.52	15.37	14.95 ± 0.10 ^h	74.10	76.30	75.20 ± 0.08 ^h
T ₅	30.42	32.72	31.57 ± 0.29 ^g	14.73	15.59	15.16 ± 0.10 ^g	74.32	76.56	75.44 ± 0.08 ^g
T ₆	30.63	32.96	31.80 ± 0.29 ^f	14.95	15.83	15.39 ± 0.10 ^f	74.49	76.84	75.67 ± 0.08 ^f
T ₇	30.85	33.15	32.00 ± 0.29 ^e	15.09	16.09	15.59 ± 0.10 ^e	74.68	77.03	75.86 ± 0.08 ^e
T ₈	30.89	33.19	32.04 ± 0.29 ^d	15.11	16.14	15.63 ± 0.10 ^d	74.73	77.10	75.92 ± 0.08 ^d
T ₉	31.08	33.41	32.25 ± 0.29 ^c	15.29	16.31	15.80 ± 0.10 ^c	74.92	77.32	76.12 ± 0.08 ^c
T ₁₀	31.10	33.46	32.28 ± 0.29 ^b	15.32	16.35	15.84 ± 0.10 ^b	74.94	77.38	76.16 ± 0.08 ^b
T ₁₁	31.27	33.66	32.47 ± 0.29 ^a	15.47	16.54	16.01 ± 0.10 ^a	75.11	77.57	76.34 ± 0.08 ^a
SE _D	0.07	0.08		0.06	0.07		0.07	0.08	
CD (p=0.05)	0.14	0.16		0.13	0.15		0.15	0.17	

In each column, means followed by the same superscript letter are not significantly different ($p \leq 0.05$) according to Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV %) represents the relative experimental variability, with lower values indicating greater precision.

vermicompost along with 100 % N fertilizer (18–20).

Conclusion

The advancement of technology for biofortification in coastal ecosystems offers significant potential for improving human health. With the use of technologies like genetic engineering, precision agriculture and biotechnology, we can enhance the nutritional quality of crops grown in coastal regions, combating prevalent micronutrient deficiencies. This innovative approach not only enhances food security but also helps prevent malnutrition and associated health issues. Furthermore, incorporating bioactive compounds provides additional protective benefits, promoting overall well-being. As we continue to progress in these technologies, sustainable solutions for enhancing human health in coastal ecosystems become increasingly achievable. Our investigation clearly demonstrates the beneficial role of fortifying organic manures and employing specific application methods alongside bioactive compounds to increase brinjal production in coastal saline soil. The recommended treatment, comprising 150 % NPK + Zn and Fe fortified CCP at 6.25 t/ha + ZnSO₄ and FeSO₄ at 3.75 kg/ha, along with foliar spray of ZnSO₄ & FeSO₄ at 0.5 %, NAA at 50 ppm, HA and SWE at 0.2 % during vegetative and flowering stages, was found to be the most effective combination for brinjal growers in coastal regions. This treatment not only maximizes net profit in brinjal yield but also sustains soil health, alleviates salinity stress and addresses human nutrient deficiencies, contributing to improved overall health outcomes.

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Authors' contributions

RK conducted the field experiments and laboratory analysis and curated the data. DE performed the data analysis and drafted the

manuscript. Both authors contributed to the conceptualization and methodology of the study, reviewed and edited the manuscript, supervised the work and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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