



RESEARCH ARTICLE

Effect of zinc application on yield, dry matter production, nutrient uptake and soil available nutrients in bhendi (*Abelmoschus esculentus* (L.) Moench)

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Abstract

The field experiment was carried out at Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, during the Rabi season of 2025 to investigate the influence of different zinc sources, application rates and methods on the growth, yield and quality of bhendi. Among the treatments, the integrated application of Zinc-Ethylendiaminetetraacetic Acid (Zn-EDTA) at 1.0 kg ha⁻¹ as basal soil application combined with a 0.1 % foliar spray at 30 days after sowing (DAS), along with recommended dose of fertilizer (RDF) and farmyard manure (FYM), produced the highest fresh fruit yield (19.33 t ha⁻¹), representing a more than three-fold increase compared to the control (5.43 t ha⁻¹). This treatment also enhanced nutrient uptake (N, P, K, Zn, Fe, Mn and Cu), indicating improved assimilation and nutrient-use efficiency. Post-harvest soil analysis revealed a balanced nutrient status, with higher Diethylene Triamine Penta acetic Acid (DTPA)-extractable micronutrient content at increased Zn-EDTA soil application levels, ensuring soil fertility sustainability. The findings highlight that integrated zinc management, particularly the use of chelated zinc, not only improves bhendi yield and quality but also enhances nutrient uptake and maintains soil nutrient balance, thereby serving as a viable strategy for boosting productivity and profitability of bhendi under intensive cultivation systems as demonstrated in the present study conducted under a randomized block design (RBD).

Keywords: bhendi; chelated zinc; micronutrient; nutrient management; zinc

Introduction

Soil fertility remains the foundation of global food production and its steady decline poses a major challenge to meeting the nutritional demands of a growing population. As agricultural systems intensify, the depletion of essential nutrients particularly micronutrients has become increasingly widespread. Among the various soil attributes, fertility holds a special significance as it determines the capacity of soil to sustain plant growth and crop production. The development and productivity of crops largely depend on the adequate supply of both macronutrients and micronutrients. Ensuring soil health and sustainability therefore requires proper soil management practices, including judicious application of fertilizers and organic matter.

Bhendi (*Abelmoschus esculentus* (L.) Moench), a member of the family Malvaceae, is an economically important vegetable crop widely cultivated in tropical and subtropical regions. Its tender pods are rich in water (88.6 g/100 g), carbohydrates (8.2 g), protein (2.1 g), fibre (1.7 g), minerals such as calcium (84 mg), phosphorus (90 mg) and iron (1.2 mg), as well as vitamins like niacin (0.6 mg), ascorbic acid (47 mg) and β -carotene (185 μ g) (1),

making it nutritionally significant.

However, soil fertility varies considerably across regions. While certain soils are naturally unproductive, others have witnessed a decline in fertility due to degradation and continuous intensive cultivation and its decline poses a significant challenge to global food security, particularly as the world population is projected to reach 9.7 billion by 2050 (2).

Zinc (Zn) is an essential nutrient for all living organisms (3). It is required in six different classes of enzyme oxidation, including oxidoreductases, transferase, hydrolyse, lyase, isomerase and ligase. Zinc has been viewed as an essential micronutrient for metabolic activities in plants and animals including human being, of which its deficiency, does not cause, physiological imbalance, enzyme activity and other metabolic processes (4). Zinc may also be required for the formation of chlorophyll, pollen grain function and fertilization (5). In addition, Zinc has important functions in the synthesis of auxin or indole acetic acid (IAA) from tryptophan and other biochemical reactions needed for chlorophyll, carbohydrate formations, regulation of stomata functions by potassium content of the guard cells. Deficiency of Zn can affect

the crop yield and quality of crops (6).

In recent years, zinc deficiency has emerged as a major soil fertility issue in the Karaikal region of the Union Territory of Puducherry. The problem is primarily attributed to the coastal alluvial nature of the soils, high pH, low organic matter content and intensive cultivation practices, all of which reduce the availability of zinc. This deficiency not only impairs fruit yield and quality but also threatens long-term soil health and sustainability. In this context, appropriate nutrient management practices, with special emphasis on micronutrient management, are essential to enhance productivity and ensure sustainable farming. Keeping these considerations in view, the present investigation was undertaken to evaluate the role of zinc fertilization strategies in improving crop performance and soil fertility.

Materials and Methods

A field experiment was carried out during the Rabi season (February-May 2025) in the eastern field (E1) of the Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, to evaluate the effect of zinc application on the yield and yield attributes of bhendi (*Abelmoschus esculentus* (L.) Moench). The site is located about 9 km northwest of Karaikal, lying between 10°95' and 11°00' N latitude and 79°43' and 79°78' E longitude. The soil of the experimental field belongs to the Surakudy soil series and is classified taxonomically as a Fluventic Haplustept.

The bhendi hybrid CO 4 was used as the test crop. Bhendi hybrid CO 4 is a high-yielding variety developed from the cross BHD 9 × Karamadai local. The crop has a duration of about 110 days. One of the notable advantages of this hybrid is its resistance to bhendi yellow mosaic virus (BYMV), making it a reliable choice for cultivation in regions prone to this disease.

Table 1. Treatment details

Treatment No	Treatment Details
T ₁	Absolute Control
T ₂	RDF + FYM at 40 t ha ⁻¹
T ₃	T ₂ + Zn EDTA at 1 kg ha ⁻¹ (SA)
T ₄	T ₂ + Zn EDTA at 1.25 kg ha ⁻¹ (SA)
T ₅	T ₂ + ZnSO ₄ at 15 kg ha ⁻¹ (SA)
T ₆	T ₂ + ZnSO ₄ at 20 kg ha ⁻¹ (SA)
T ₇	T ₃ + Zn EDTA at 0.1 % (FA)
T ₈	T ₅ + ZnSO ₄ at 0.5 % (FA)

The experiment was laid out in a randomized block design (RBD) with eight treatments and three replications. The treatments details are comprised in Table 1.

The recommended dose of fertilizers (RDF) was 200:100:100 kg ha⁻¹ of N, P₂O₅ and K₂O, applied through urea, single superphosphate (SSP) and muriate of potash (MOP) respectively (7). Nitrogen was applied in two equal splits 50 % as basal and the remaining 50 % at 30 DAS. Farmyard manure (FYM) was incorporated at 40 t ha⁻¹ as basal. Zinc sulphate and zinc ethylenediaminetetraacetic acid (Zn-EDTA) were applied either as basal soil application or as foliar sprays at 30 DAS, depending on the treatment. The crop was sown on ridges at a spacing of 60 × 45 cm. First irrigation was given on the third day after sowing, followed by irrigations as required. Gap filling was done at 7 DAS and thinning at 15 DAS. Weed management included pre-emergence application of

pendimethalin 30 EC (on third day after sowing) and hand weeding whenever necessary. Harvesting of tender fruits commenced from 45 DAS at alternate-day intervals. For biometric observations, five plants per plot were randomly selected and tagged. Post-harvest, surface soil samples (0–15 cm) were collected from all plots, air-dried, sieved (2 mm) and analysed for pH, electrical conductivity (EC), organic carbon and available N, P, K and DTPA-extractable Zn, Fe, Mn and Cu. Yield components were recorded at three stages, viz., the 5th picking (52 DAS), 12th picking (67 DAS) and the final picking (22nd picking, 97 DAS), to assess early, peak and late harvest performance, ensuring a comprehensive and accurate yield evaluation. The values obtained at these stages were averaged to derive the overall yield performance. Representative plant and fruit samples were collected, oven-dried at 60 °C to constant weight, powdered and analysed for nutrient content.

The analytical procedures used for soil and plant analysis followed standard, widely accepted methodologies. Physico-chemical properties such as soil pH and electrical conductivity were determined in a 1:2.5 soil-water suspension using potentiometry and conductometry, respectively (8). Organic carbon was estimated using the chromic acid wet digestion method (9). Available nitrogen was measured by the alkaline permanganate method (10), available phosphorus using the Bray and Kurtz (11) extractant using spectrophotometer and available potassium using neutral normal ammonium acetate followed by flame photometry (12). Micronutrients were extracted using the DTPA method (13) using Microwave Plasma-Atomic Emission Spectroscopy (MP-AES) instrument. Plant samples were analysed following diacid extraction using a sulphuric-perchloric acid mixture for nitrogen estimation (14). Phosphorus content in plant tissues was determined using the Vanado-molybdate yellow colour method with triple-acid extract (8), while potassium was estimated by flame photometry using neutralised triacid extracts. Micronutrient concentrations in plant samples were also determined using the triacid extract (13).

The experimental data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for RBD using AGRES software. Wherever treatment effects were significant, critical difference (CD) at 5 % probability was computed to compare means.

Results and Discussion

Soil characterisation of the experimental field

The experimental soil belonged to the Sorakudy soil series and was classified taxonomically as Fluventic Haplustept. Characterization of the soil indicated no major constraints to crop production, except deficiencies of nitrogen, phosphorus and zinc. The soil texture was sandy clay loam, comprising 65.65 % sand, 7.50 % silt and 25.90 % clay. The soil reaction was slightly acidic (pH 5.85), with a non-saline electrical conductivity (0.08 dS m⁻¹). Among the exchangeable bases, the order of dominance was Ca > Mg > Na > K.

The organic carbon content was low (0.49 %). Regarding available macronutrients, the soil was low in available nitrogen (136 kg ha⁻¹; alkaline KMnO₄ method) and phosphorus (17 kg ha⁻¹; Bray's P₁ extraction), while available potassium (141 kg ha⁻¹; NH₄OAc extraction) was in the medium range.

Effect of zinc and farmyard manure on fruit yield and dry matter production

The statistical analysis indicated that fruit yield of bhendi was significantly influenced by zinc nutrition in combination with inorganic fertilizers and FYM. The highest yield (19.33 t ha⁻¹) was recorded with the application of Zn-EDTA at 1.0 kg ha⁻¹ as basal soil application in conjunction with a foliar spray of Zn-EDTA at 0.1 % at 30 DAS, along with RDF and FYM. This treatment was in association with the application of ZnSO₄ at 15 kg ha⁻¹ as soil application plus a foliar spray of ZnSO₄ at 0.5 % (18.55 t ha⁻¹). A deeper synthesis of these findings shows that the superior performance of the Zn-EDTA treatment (T7) can be attributed to the inherent advantages of chelated zinc. Zinc ethylenediaminetetraacetic acid remains more stable in soil, resists fixation and provides a steady supply of bioavailable zinc throughout the crop growth period. This continuous availability likely enhanced auxin synthesis, enzymatic activities and efficient nutrient uptake, which together translated into improved pod formation and overall yield. In contrast, the absolute control registered the lowest yield (5.43 t ha⁻¹), clearly demonstrating the critical role of integrated zinc management in enhancing bhendi productivity.

A similar trend was observed in dry matter production in plant. The highest dry matter accumulation (3389 kg ha⁻¹) was achieved with Zn-EDTA at 1 kg ha⁻¹ + foliar spray at 0.1 % in conjunction with RDF + FYM, which was statistically comparable to ZnSO₄ at 15 kg ha⁻¹ + foliar spray at 0.5 % (3189 kg ha⁻¹). The control plot recorded the lowest dry matter production of 1674 kg ha⁻¹.

With respect to mean dry matter production in fruit, Zn-EDTA at 1 kg ha⁻¹ + foliar spray at 0.1 % with RDF + FYM resulted in the highest value (303 kg ha⁻¹), which was significantly superior to all other treatments. This was followed by ZnSO₄ at 15 kg ha⁻¹ + foliar spray at 0.5 % (274 kg ha⁻¹). The minimum mean dry matter production (226 kg ha⁻¹) was observed under the control (Table 2).

The enhanced yield of okra observed with Zn-EDTA application may be attributed to its superior solubility, stability

and bioavailability when compared with inorganic zinc sources such as ZnSO₄. As a chelated compound, Zn-EDTA minimizes zinc fixation in the soil and maintains a steady supply of available Zn in the rhizosphere (15). This ensures efficient root absorption and facilitates better translocation of zinc to actively growing plant parts, thereby promoting improved growth and yield performance. Similar findings were reported (16), who highlighted the effectiveness of Zn-EDTA in enhancing crop productivity. The increase in fresh and dry weight of okra plants might be attributed to the vital role of zinc in chlorophyll formation, cell division, meristematic activity and cell expansion. Zinc also promotes the active synthesis of tryptophan, the primary precursor of auxin, which stimulates plant tissue growth, thereby enhancing fresh weight and ultimately contributing to higher dry matter accumulation (17). Similar findings were reported earlier (18) reported that balanced nutrient management significantly enhanced plant height, leaf area and dry matter production in okra, further confirming that adequate micronutrient supply including zinc directly contributes to improved growth and biomass.

Influence of zinc fertilization on nutrient uptake

Nutrient uptake by bhendi fruit was significantly influenced by zinc application along with fertilizers and FYM. The treatment with Zn-EDTA at 1 kg ha⁻¹ as soil application + foliar spray at 0.1 % in combination with RDF and FYM recorded the highest uptake of N (8.34 kg ha⁻¹), P (6.19 kg ha⁻¹), K (8.11 kg ha⁻¹), Zn (18.16 g ha⁻¹), Fe (3.82 g ha⁻¹), Mn (2.46 g ha⁻¹) and Cu (2.99 g ha⁻¹). These values were in conjunction with ZnSO₄ at 15 kg ha⁻¹ as soil application + foliar spray at 0.5 % with RDF and FYM, which recorded N (7.31 kg ha⁻¹), P (3.54 kg ha⁻¹), K (7.08 kg ha⁻¹), Zn (16.47 g ha⁻¹), Fe (3.43 g ha⁻¹), Mn (2.20 g ha⁻¹) and Cu (2.41 g ha⁻¹). The lowest nutrient uptake was consistently observed in the control plot, with N (4.19 kg ha⁻¹), P (0.37 kg ha⁻¹), K (2.72 kg ha⁻¹), Zn (12.80 g ha⁻¹), Fe (2.70 g ha⁻¹), Mn (1.61 g ha⁻¹) and Cu (0.87 g ha⁻¹) (Table 3).

The nutrient uptake by the plant was markedly influenced by zinc fertilization in combination with RDF and FYM. The application of Zn-EDTA at 1 kg ha⁻¹ as soil application with foliar spray at 0.1 % recorded the highest uptake of nitrogen (57.89 kg ha⁻¹)

Table 2. Effect of zinc, inorganic fertilizers and farmyard manure on the yield and dry matter production (DMP)

T. No	Treatment Details	Yield (t ha ⁻¹)	DMP in plant (kg ha ⁻¹)	DMP in fruit (kg ha ⁻¹)
T ₁	Absolute Control	5.43	1674	226
T ₂	RDF + FYM at 40 t ha ⁻¹	13.06	2252	248
T ₃	T ₂ + Zn EDTA 1 kg ha ⁻¹ (SA)	16.96	2779	257
T ₄	T ₂ + Zn EDTA 1.25 kg ha ⁻¹ (SA)	17.33	3034	267
T ₅	T ₂ + ZnSO ₄ 15 kg ha ⁻¹ (SA)	14.92	2628	250
T ₆	T ₂ + ZnSO ₄ 20 kg ha ⁻¹ (SA)	17.29	2878	263
T ₇	T ₃ + Zn EDTA 0.1 % (FA)	19.33	3389	303
T ₈	T ₅ + ZnSO ₄ 0.5 % (FA)	18.55	3189	274
Mean		15.36	2728	261
S. Ed		0.09	162	2
C.D. (0.05)		0.21	323	4

Table 3. Effect of zinc, inorganic fertilizers and farmyard manure on uptake of nutrients by fruit

T. No	Treatment Details	N uptake (kg ha ⁻¹)	P uptake (kg ha ⁻¹)	K uptake (kg ha ⁻¹)	Zn uptake (g ha ⁻¹)	Fe uptake (g ha ⁻¹)	Mn uptake (g ha ⁻¹)	Cu uptake (g ha ⁻¹)
T ₁	Absolute Control	4.19	0.37	2.72	12.80	2.70	1.61	0.87
T ₂	RDF + FYM at 40 t ha ⁻¹	5.14	1.18	4.02	14.26	3.01	1.82	1.19
T ₃	T ₂ + Zn EDTA 1 kg ha ⁻¹ (SA)	6.27	1.95	5.81	14.95	3.17	1.95	1.75
T ₄	T ₂ + Zn EDTA 1.25 kg ha ⁻¹ (SA)	6.90	2.95	6.58	15.89	3.32	2.10	2.08
T ₅	T ₂ + ZnSO ₄ 15 kg ha ⁻¹ (SA)	5.99	1.76	4.87	14.50	3.06	1.86	1.57
T ₆	T ₂ + ZnSO ₄ 20 kg ha ⁻¹ (SA)	6.56	2.36	6.34	15.59	3.26	2.02	1.92
T ₇	T ₃ + Zn EDTA 0.1 % (FA)	8.34	6.19	8.11	18.16	3.82	2.46	2.99
T ₈	T ₅ + ZnSO ₄ 0.5 % (FA)	7.31	3.54	7.08	16.47	3.43	2.20	2.41
Mean		6.34	2.54	5.69	15.33	3.22	2.00	1.85
S. Ed		0.07	0.05	0.09	0.20	0.10	0.05	0.21
C.D. (0.05)		0.14	0.11	0.18	0.41	0.20	0.11	0.43

Table 4. Effect of zinc, inorganic fertilizers and farmyard manure on uptake of nutrients by plant

T. No	Treatment Details	N uptake (kg ha ⁻¹)	P uptake (kg ha ⁻¹)	K uptake (kg ha ⁻¹)	Zn uptake (g ha ⁻¹)	Fe uptake (g ha ⁻¹)	Mn uptake (g ha ⁻¹)	Cu uptake (g ha ⁻¹)
T ₁	Absolute Control	29.08	18.72	22.13	64.96	49.75	49.45	28.55
T ₂	RDF + FYM at 40 t ha ⁻¹	38.08	25.05	29.51	112.08	82.82	75.68	42.23
T ₃	T ₂ + Zn EDTA 1 kg ha ⁻¹ (SA)	46.32	30.99	35.93	118.49	89.44	83.70	52.39
T ₄	T ₂ + Zn EDTA 1.25 kg ha ⁻¹ (SA)	50.92	34.22	39.47	131.50	100.89	91.52	59.40
T ₅	T ₂ + ZnSO ₄ 15 kg ha ⁻¹ (SA)	43.81	29.13	34.10	113.90	83.26	79.05	49.52
T ₆	T ₂ + ZnSO ₄ 20 kg ha ⁻¹ (SA)	48.14	32.34	37.36	123.64	93.93	85.70	55.43
T ₇	T ₃ + Zn EDTA 0.1 % (FA)	57.89	38.88	44.55	147.88	110.94	104.64	65.63
T ₈	T ₅ + ZnSO ₄ 0.5 % (FA)	54.34	36.28	41.78	139.54	107.53	95.56	64.47
Mean		46.07	30.70	35.60	119.00	89.82	83.16	52.20
S. Ed		2.13	1.60	1.64	5.24	4.82	4.91	3.53
C.D. (0.05)		4.24	3.19	3.27	10.45	9.62	9.80	7.04

¹), phosphorus (38.88 kg ha⁻¹), potassium (44.55 kg ha⁻¹), zinc (147.88 g ha⁻¹), iron (110.94 g ha⁻¹), manganese (104.64 g ha⁻¹) and copper (65.63 g ha⁻¹). These values were statistically comparable to with ZnSO₄ at 15 kg ha⁻¹ as soil application + foliar spray at 0.5 %, which registered N (54.34 kg ha⁻¹), P (36.28 kg ha⁻¹), K (41.78 kg ha⁻¹), Zn (139.54 g ha⁻¹), Fe (107.53 g ha⁻¹), Mn (95.56 g ha⁻¹) and Cu (64.47 g ha⁻¹). The untreated control showed the least nutrient uptake, with N (29.08 kg ha⁻¹), P (18.72 kg ha⁻¹), K (22.13 kg ha⁻¹), Zn (64.96 g ha⁻¹), Fe (49.75 g ha⁻¹), Mn (49.45 g ha⁻¹) and Cu (28.55 g ha⁻¹) thereby highlighting the significant role of integrated zinc management in improving plant nutrient acquisition (Table 4).

In bhendi, higher nutrient uptake has been closely associated with increased dry matter accumulation and fruit yield due to better nutrient utilization efficiency (19). The synergistic effect of FYM with Zn-EDTA results in a higher concentration of nutrient of okra, thereby improving pod quality and yield.

Foliar application of chelated zinc has proven to be a more efficient strategy for improving both yield and nutritional quality compared to inorganic zinc sources. Foliar Zn-EDTA application was markedly more effective in raising grain zinc concentration along with other essential nutrient levels in common beans (20).

FYM application with balanced fertilization increased P availability by reducing fixation and improving soil biological activity (21). In addition, applied NPK resulted in better root growth and increased physiological activity of roots to absorb more phosphorus. These findings are in conformity (22) in okra. Balanced NPK fertilization ensures adequate nutrient in the soil and in the presence of FYM and Zn-EDTA, its utilization efficiency is improved, resulting in higher uptake (23, 24).

This improvement may be attributed to the multiple roles played by FYM and Zn in enhancing Fe availability and uptake. FYM enriches the soil organic matter and produces organic acids during decomposition, which chelate Fe and prevent its oxidation and precipitation as insoluble hydroxides, thereby maintaining in plant available forms (25).

Effect of post-harvest soil nutrient status

The soil pH was not influenced by the application of Zn, RDF, FYM, or their interactions. However, electrical conductivity (EC) varied among treatments. Soil organic carbon did not differ significantly among the treatments. This may be attributed to the inherent buffering capacity of the soil, which resists short-term changes in reaction (pH) despite external nutrient inputs. Similarly, soil organic carbon is relatively stable in nature and tends to show noticeable changes only under long-term organic matter additions. While FYM application contributed organic inputs, the short duration of the experiment and

the rapid mineralization of applied organic matter under tropical conditions could have limited its impact on measurable organic carbon content. When Zn-EDTA or ZnSO₄ were applied as sole treatments, there was no significant increase in pH (26).

The integrated application of Zn EDTA at 1 kg ha⁻¹ as soil application combined with 0.1 % foliar spray along with RDF and FYM proved highly effective in improving soil nutrient availability. This treatment recorded the maximum KMnO₄-N (166.02 kg ha⁻¹), Bray's phosphorus (30.79 kg ha⁻¹) and NH₄OAc- K (163.55 kg ha⁻¹), all of which were significantly superior compared to other treatments. These values were in conjunction with ZnSO₄ at 15 kg ha⁻¹ as soil application with 0.5 % foliar spray along with RDF and FYM, which registered 164.84 kg ha⁻¹ of KMnO₄-N, 30.28 kg ha⁻¹ of Bray-P and 160.83 kg ha⁻¹ of NH₄OAc- K. In contrast, the absolute control consistently recorded the lowest nutrient availability, with 127.18 kg ha⁻¹ of KMnO₄-N, 13.24 kg ha⁻¹ of Bray-P and 119.83 kg ha⁻¹ of NH₄OAc- K.

The observed increase in available N, P and K by 13.55 %, 35.70 % and 7.50 % respectively in the post-harvest soil over the initial soil status can be attributed to the synergistic effect of the imposed treatments, which involved the combined application of organic manures (FYM) and fertilizers along with zinc management.

Micronutrient availability in soil was significantly enhanced by the application of Zn sources and levels, particularly with Zn-EDTA. The treatment Zn-EDTA at 1.25 kg ha⁻¹ as soil application along with RDF and FYM consistently registered the highest values for DTPA extractable micronutrients, recording 2.89 mg kg⁻¹ of zinc, 83.45 mg kg⁻¹ of iron, 16.17 mg kg⁻¹ of manganese and 0.98 mg kg⁻¹ of copper. These values were statistically comparable to those obtained with Zn-EDTA at 1 kg ha⁻¹ + RDF + FYM, which registered 2.04, 83.32, 16.05 and 0.93 mg kg⁻¹ of Zn, Fe, Mn and Cu respectively. In contrast, the absolute control consistently recorded the lowest availability of micronutrients, with values of 1.08, 38.78, 10.89 and 0.75 mg kg⁻¹ for Zn, Fe, Mn and Cu, respectively (Table 5). This clearly highlights the superiority of Zn-EDTA application in improving soil micronutrient status compared to untreated or sole RDF + FYM practices.

Farmyard manure improves soil organic matter and microbial activity, which further enhances micronutrient solubility and uptake by plants (27). Farmyard manure contributes organic acids during decomposition, which chelate and prevent its fixation, thereby enhancing its solubility and availability to plants (28).

The DTPA extractable micronutrients Zn, Fe, Mn and Cu showed an increase of 45.45 %, 52.63 %, 28.96 % and 3.44 % respectively in the post-harvest soil over the initial soil status because of treatment imposition. This could be attributed due to native soil status, nutrient content of FYM and its synergistic effect of combined application. Integrating zinc (Zn), inorganic fertilizers

Table 5. Effect of zinc, inorganic fertilizers and farmyard manure on soil properties on post-harvest soil

T. No	Treatment Details	pH	EC (dS m ⁻¹)	OC (%)	KMnO ₄ -N (kg ha ⁻¹)	Bray-P (kg ha ⁻¹)	NH ₄ OAc-K (kg ha ⁻¹)	DTPA-Zn (mg kg ⁻¹)	DTPA-Fe (mg kg ⁻¹)	DTPA-Mn (mg kg ⁻¹)	DTPA-Cu (mg kg ⁻¹)
T ₁	Absolute Control	5.87	0.19	0.57	127.18	13.24	119.83	1.08	38.78	10.89	0.75
T ₂	RDF + FYM at 40 t ha ⁻¹	5.86	0.12	0.56	152.27	24.69	143.83	1.55	81.38	15.87	0.78
T ₃	T ₂ + Zn EDTA 1 kg ha ⁻¹ (SA)	5.87	0.19	0.53	160.67	27.7	157.19	2.04	83.32	16.05	0.93
T ₄	T ₂ + Zn EDTA 1.25 kg ha ⁻¹ (SA)	5.88	0.20	0.56	163.47	29.43	161.33	2.89	83.45	16.17	0.98
T ₅	T ₂ + ZnSO ₄ 15 kg ha ⁻¹ (SA)	5.87	0.19	0.55	160.67	26.47	153.45	1.86	81.79	15.89	0.90
T ₆	T ₂ + ZnSO ₄ 20 kg ha ⁻¹ (SA)	5.86	0.11	0.55	163.44	28.92	159.57	1.95	81.90	15.92	0.90
T ₇	T ₃ + Zn EDTA 0.1 % (FA)	5.87	0.10	0.55	166.02	30.79	163.55	1.96	81.93	15.97	0.93
T ₈	T ₅ + ZnSO ₄ 0.5 % (FA)	5.86	0.19	0.56	164.84	30.28	160.83	1.60	81.73	15.88	0.78
Mean		5.87	0.16	0.55	157.32	26.44	152.44	1.87	76.79	15.33	0.87
S. Ed		0.008	0.009	0.005	0.83	0.16	1.19	0.10	0.34	0.10	0.01
C.D. (0.05)		NS	0.019	NS	1.65	0.33	2.38	0.20	0.69	0.20	0.03

(NPK) and FYM leads to substantial improvements in soil quality. Long-term studies show that this combination increases soil organic carbon, available nitrogen, phosphorus, potassium and micronutrients (including Zn, Cu, Fe, Mn and B), while maintaining or slightly reducing soil pH and electrical conductivity (29, 30). The use of FYM with Zn and NPK enhances cation exchange capacity, water holding capacity and soil porosity and reduces bulk density, all of which contribute to better soil structure and fertility (31).

Conclusion

Overall, the investigation clearly established the vital role of balanced zinc nutrition in enhancing the growth, productivity and nutrient dynamics of bhendi under intensive cropping conditions. The integrated nutrient management approaches evaluated in this study highlighted the superiority of chelated zinc sources in ensuring sustained availability of the nutrient throughout the crop growth period. The study demonstrated that the integrated application of Zn-EDTA at 1.0 kg ha⁻¹ as basal soil application, in combination with RDF (200:100:100 NPK kg ha⁻¹) and FYM at 40 t ha⁻¹, along with a foliar spray of Zn-EDTA at 0.1 % at 30 DAS, significantly enhanced the yield and dry matter production of bhendi. The improvement in yield and yield components can be ascribed to improved zinc availability, which promoted auxin metabolism, pollen formation, enzymatic activity and efficient translocation of photosynthates. Therefore, the adoption of Zn-EDTA at 1.0 kg ha⁻¹ together with a 0.1 % foliar spray, along with RDF and FYM, emerges as a highly effective strategy to improve fruit yield, nutrient uptake and soil nutrient status in bhendi, while simultaneously addressing zinc deficiency in soils under intensive cultivation.

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Authors' contributions

MV designed the study. VN experimented and drafted the manuscript. SM, KS, TA and JD assisted in analysing and drafting

the manuscript's final version and MP and PT did the statistical analysis. All authors read and approved the final manuscript

Compliance with ethical standards

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