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Critical micro and secondary nutrient deficiency and its supplementation influencing ginger production and quality in Eastern Ghat highland agroclimatic zone

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Abstract

The Eastern Ghat Highland Agroclimatic Zone, covering major part of Koraput and Nabarangpur, has a warm, humid climate and hilly terrain at 900–1400 m MSL, favorable for spice crops like ginger. However, due to traditional farming methods by tribal communities, productivity remains low at 4.9 t/ha. Hence, an experiment was conducted in Pottangi, Koraput, to improve ginger yield by addressing secondary and micronutrient deficiencies (S, Zn, B) identified by the AICRP in local soils. The study tested ten treatments involving organic, inorganic, and foliar applications of secondary and micronutrients in light-textured, acidic sandy loam soil with low S, B, Zn but high Fe, Mn, and Cu. The ginger variety "Suprava" was cultivated, and foliar sprays were taken up at 60 and 90 days after planting. Significant improvements in plant growth parameters, such as height, tiller count, and leaf number, were observed with the nutrient treatments compared to recommended dose of fertilizer (RDF). The highest rhizome yield (14.3 t /ha) was obtained with Zn + S, followed by IISR micronutrient foliar spray, while the lowest yield was from inorganic RDF. Organic treatments yielded better than inorganic, and combined or sole applications of secondary and micronutrients, particularly foliar sprays, enhanced yield and quality metrics like TSS, fibre, phenol, and protein contents. Regression analysis indicated a 98% influence of N, P, K, S, Zn, and B uptake on yield, underscoring the importance of supplementing deficient nutrients to improve yield, quality, and soil health.

Keywords: Zinc, boron, sulphur, ginger, production, high altitude

Introduction

India with its diverse agroclimatic conditions supports the cultivation of numerous crops, including ginger (*Zingiber officinale* Roscoe), a key spice with low productivity due to poor management practices, soil erosion, and pest pressures. Farmers of hilly regions often plant ginger along slopes, leading to erosion during monsoons and reduced soil fertility, with unregulated chemical fertilizers commonly used in the absence of recommended protocols.

Ginger is native to Southeast Asia, likely India or China, and was historically spread through trade to the Mediterranean and Africa, now produced primarily by China, Taiwan, India, the Philippines, Jamaica, and Nigeria. In India, Madhya Pradesh leads in production, followed by Kerala and Karnataka. Ginger is valued for its unique flavour, applied across food, pharmaceutical, and fragrance industries, and medicinal property for benefits in digestion, nausea, and headaches (Dedov *et al.*, 2002), with antioxidant, antibacterial, and immunomodulatory properties (Vimala *et al.*, 1999; Akoachere *et al.*, 2002).

India is the largest global producer of ginger, contributing 42% of the world's area and 38.15% of production in 2023 (FAOSTAT, 2021). It is cultivated in 160,000 ha, yielding 758,851 tonnes. The country produces around 22.89 percent of ginger of the world. Odisha, with 16.6 thousand ha, produces 193,000 tonnes, but productivity is low at 1.9 t/ha, compared to the national average of 6.98 t/ha (HSG, 2018). Improving productivity involves optimizing factors such as cultivar choice, planting dates, climate, nutrient management, and maturation times (Behera *et al.*, 2020).

Micronutrients, though required in trace amounts, are critical to crop growth and development, with several crops responding positively to their application (Barbosa *et al.*, 2016; Alkarawi & Hasan, 2021). In ginger, micronutrient treatments have shown yield increases from 29.4% to 125.1% (Singh & Dwivedi, 2007). Zinc and boron, in particular, significantly enhance ginger yield (Halder *et al.*, 2007). Despite positive results in other crops, ginger has received limited attention in micronutrient research, presenting an opportunity for further study.

Ginger is a key cash crop for tribal farmers in Odisha, the second-largest producer by area in India and with favorable growing conditions second only to Kerala (Parthasarathy *et al.*, 2008). Ginger, a nutrient-intensive crop, requires both macro- and micronutrients for optimal growth. Micronutrients, although required in smaller amounts, are critical for plant health and productivity, and deficiencies in zinc (Zn), boron (B), and sulphur (S) commonly impact ginger crop (Parthasarathy *et al.*, 2010).

Zinc promotes growth and quality by facilitating essential functions like protein synthesis, gene expression, and photosynthesis, while boron supports cell structure and enhances cell division and metabolism (Marschner, 1997). Boron deficiency hinders rhizome quality by limiting metabolite and essential oil translocation to the rhizome (Dixit *et al.*, 2002). Studies indicate that micronutrients, particularly Zn, Fe, and B, significantly improve ginger yield and quality (Roy *et al.*, 1992). Rapid foliar absorption of these nutrients further enhances plant response and productivity (Baloch *et al.*, 2008).

The soils of Koraput, a major ginger-growing area, lack sufficient Zn, B, and S (AICRP Micronutrient Report, 2017–18), which limits ginger production. This study aimed to assess the soil nutrient levels in ginger-growing soils of Koraput and determining the impact of sulphur (S), boron (B), and zinc (Zn) on both rhizome yield and quality in ginger production.

Materials and methods

Location of the study and weather parameters

The field experimentation was carried out at High Altitude Research Station, Pottangi, Koraput under Odisha University of Agriculture and Technology. It is situated in Eastern Ghat high land agroclimatic zone of Odisha and lies at latitude 18.564151N, longitude 82.968756E and altitude 943 meters above mean sea level. The land type of experimental site is high land.

Fig. 1. Location of the study area

During the crop growth period, total rainfall received was 1504 mm, with mean annual temperatures ranging from a maximum of 36.6°C in April to a minimum of 13.5°C in January.

Soil sample collection of experimental site and analysis

Surface soil samples were collected from experimental field of Pottangi block of Koraput. To assess soil fertility, initial and post-harvest soil samples (0.5 kg each) were collected from 15 cm depth using a soil auger, shade-dried, and processed. Samples were cleared of debris, crushed with a wooden hammer, and sieved through a 2 mm sieve; larger particles were discarded. Finally, samples were labelled and stored in polythene bags for physical and chemical analysis.

Analysis of the experimental soil was done following standard analytical procedures, texture (sandy loam) analysis by Bouyoucos Hydrometer method (Piper, 1950), soil pH (4.65) and EC (0.098 dS/m) by 1:2.5 soil water suspension by Jackson (1973), soil organic carbon (7.1 g/kg) by Walkley and Black rapid titration method (Jackson, 1973), available N (495 kg/ha) using the alkaline permanganate method (Subbiah and Asija, 1956), available P (33 kg/ha) using Bray's 1 extractant (Page *et al.*, 1982), available K (315 kg/ha) using flame photometer (Jackson, 1973) and available sulphur (6 kg/ha) using turbidimetric method (Chesnin and Yien, 1950). The available Fe (146 mg/kg), Mn (86.92 mg/kg), Cu (2.84 mg/kg), and Zn (0.48 mg/kg) were analysed using DTPA (Lindsay and Norvell, 1978) in AAS and the concentration of the elements was calculated (Page *et al.*, 1982). Available boron (0.45 mg/kg) was determined by hot water extraction of soil (Berger and Truog, 1939)

Collection of plant samples and analysis

Plant and rhizome samples from each plot were collected and cleaned with tap water, 0.1N HCl, and double-distilled water, then air-dried and oven-dried at 65°C. After drying to constant weight, they were crushed using a Willey mill. The samples were then ready for elemental analysis. The plant samples' nitrogen content was assessed using Jackson's micro-Kjeldahl technique (1973), phosphorus by Vanadomolybdo-phosphate yellow colour method (Jackson, 1973), total K by flame photometer, total Ca and Mg by titration using an EBT (for Ca and Mg) and calcon (for Ca) indicator against 0.01N EDTA, total sulphur and boron by spectrophotometer (Jackson, 1973). Analysis for total Fe, Mn, Cu, Zn in plant tissue was conducted as per Page *et al.*, (1982). Crude fibre was determined by digestion of the plant samples at 600°C in the muffle furnace, the total soluble solids (TSS) (o Brix) using digital refractometer, pH of ginger juice by digital pH meter at 1:2 (sample: distil water), phenol content of rhizome by Folin-ciocalteau reagent method and crude protein by micro-Kjheldahl method.

Treatments details

To know the effect of micronutrient supplementation 10 different treatments were selected, the details of which are presented below. T1- FYM (Farm yard manure@15t/ha), T2- RDF (Recommend dose of fertilizer) 125:100:100 (N – P2O5 – K2O kg / ha), RDF + Zn (2.5 kg/ha), T4- RDF+ B (1 kg / ha), T5 RDF + S (15 kg / ha), T6 - RDF + Zn@ 2.5 kg /ha+ B @ 1 kg ha, T7- RDF+ Zn @2.5 kg/ha+ S@ 15 kg/ha, T8- RDF+B @ 1 kg / ha + S @ 15 kg / ha, T9- RDF+B @ 1 kg / ha + Zn @2.5 kg / ha + S @ 15 kg / ha, T10 - RDF + IISR micronutrient mixture (power G) 5 g/L at 60 and 90 days after germination.

Results and discussion

Surface soil micro- secondary nutrient status of Pottangi, Koraput

As the roots of the majority of field crops are present in the surface soil, it influences nutrient uptake and plant growth. Therefore, surface soil samples from the Pottangi block was collected, processed, and analysed to assess nutrient status for crop management. The surface soil of the Pottangi block were acidic (5.57), non-saline (0.15 dS/m), 28% low in soil organic carbon status. Soils were deficiency in available Sulphur (7.85 mg/kg) content followed by boron (0.62 mg/kg) and zinc (1.26 mg/kg). Similar finding with respect to deficient of sulphur and zinc in the surface soil was also reported by Dixit *et al.* (2020), in mapping the nutrient status of Odisha's soils. The reason for deficiency of micro and secondary nutrients like sulphur, boron and zinc might be due to dominance of red laterite soils, rich in Al, Fe, Cu and Mn but deficient in sulphur and Zinc containing minerals, upland conditions, low clay and organic matter content.

Soil profile study of Pottangi, Koraput

Basic properties of soil like pH, EC, OC, *etc.* were analysed for experimental soil. The surface layer of the upland soil profile was extremely acidic (pH 4.19), with pH gradually increasing to 5.25 with depth. Medium land soils were strongly acidic (pH 5.38–5.54), following a similar trend. In lowland soils, pH increased from 5.03 at the surface to 5.58 with depth, likely due to leaching of bases from upper to lower layers. Electrical conductivity (EC) was highest in the top layer of upland soils, decreasing with depth across all profiles. All EC values remained below 1 dS/m, indicating non-saline conditions. Organic carbon content in the surface soil was high across upland (1.38%), medium land (0.88%), and lowland (1.36%) profiles, gradually decreasing with depth in all cases. Available sulphur (S) content in the topsoil was moderate across upland (17.94 mg/kg), medium land (15.21 mg/kg), and lowland (16.49 mg/kg) profiles, decreasing with depth. This decline corresponds with reduced organic carbon in deeper layers, as S is mineralized from organic matter. The 0–20 cm surface soil layer had medium levels of available sulphur, benefiting shallow-rooted crops, while deeper layers were low in sulphur, requiring S management for deep-rooted crops. DTPA-Fe ranged widely across soil profiles, highest in the surface layer of medium land soils (47.72–106.12 mg/kg) and lower in upland (3.24–60.48 mg/kg) and lowland (16.52– 66.08 mg/kg) soils, decreasing with depth. DTPA-Mn levels were sufficient in surface soils of upland (74.08 mg/kg), medium land (81.4 mg/kg), and lowland (30.68 mg/kg) profiles. DTPA-Zn was deficient in the top 0–20 cm layer of lowland and upland soils but sufficient in subsurface layers. Deficiencies in Fe, Mn, Zn, and Cu in upland soils were likely due to heavy rainfall causing nutrient leaching into midland and lowland areas.

Data presented in Table 1 revealed that, rhizome spread varied from 28.27 cm in FYM (T1) to highest of 30.06 cm in T9 (RDF + B + Zn +S). Spread length significantly increased in response to micronutrient fertilization and their combinations over RDF (T2) and organic only (T1). Number of fingers per rhizome varied from 8.66 in T2 (RDF) to highest of 15.33 in T7 (Zn + S) and 15.00 in T6 (Zn + B) an increase of 77.02%. It might be due to importance of B in cell wall structural integrity, cell expansion, pH regulation, transport of mineral *etc.*

Effect of S, B and Zn on rhizome yield

Effect of S, B and Zn on the rhizome yield and fresh biomass yield of ginger is presented in Table 2. Fresh rhizome yield ranged from 8.5 t/ha in RDF to 14.3 t/ha in T7 (Zn + S), a 68.2% increase over RDF. FYM treatment yielded 11.6 t/ha, outperforming RDF and single nutrient applications, while combined secondary and micronutrient applications further boosted yield. Foliar spraying of multi micronutrients mixture increased rhizome yield by 58.9%, the second-highest gain among treatments. Fresh biomass yield varied from 26.1 t/ha in RDF to 32.5 t/ha in T6 (RDF + Zn + B), with significant increases in all treatments compared to RDF alone. Similar findings was also reported by Haldar *et al.* (2007) which showed that the combined effect of boron and zinc markedly influences the rhizome yields and other yield

Table 1. Yield attributing parameters of ginger in response to micro and secondary nutrients

No.	Treatment	Rhizome spread length (cm)	Rhizome spread width (cm)	No. of fingers per rhizome
T_1	FYM (Farm yard manure @15t/ha)	28.40	2.86	11.33
T_2	RDF (Recommend dose of fertilizer) 125:100:100 (N – P_2O_5 – K_2O kg/ha)	28.27	2.86	8.66
T_3	RDF + Zn (2.5 kg/ha)	29.46	3.16	9.33
T_4	RDF + B (1 kg/ha)	30.23	3.06	11.67
T_5	RDF + S (15 kg/ha)	30.03	3.10	12.33
T_6	RDF + Zn @ 2.5 kg/ha + B @ 1 kg/ha	30.03	3.16	15.00
T_7	RDF + Zn @ 2.5 kg/ha + S @ 15 kg/ha	28.60	3.13	15.33
T_8	RDF + B @ 1 kg/ha + S @ 15 kg/ha	29.90	2.93	12.66
T_9	RDF + B @ 1 kg/ha + Zn @ 2.5 kg/ha + S @ 15 kg/ha	30.06	3.06	12.33
T_{10}	RDF + IISR micronutrient mixture (power G) 5 g/l at 60 and 90 days after germination	30.10	3.10	11.33
	SE. m (±)	0.48	0.043	1.412
	CD (P=0.05)	1.44	0.128	NS

attributes of ginger. Hamza *et al.* (2012) also reported that the addition of Zn enhanced fresh ginger production from 7.72 to 9.57 kg $3m^{-2}$, a 23% increase. Melati *et al.* (2016) reported that the improvement in rhizome yield due to boron which increased the pollen viability. Yousuf *et al.* (2013) also obtained highest yield by application of S @ 15 kg/ha along with RDF. Jabborova *et al.* (2021) reported similar influence of micronutrients on rhizome yield due to increase in enzyme activity by application of micronutrients.

Influence of S, B and Zn on quality attributes of ginger

The effect of micronutrients on quality attributes such as pH, TSS, crude fibre, crude protein and phenol *etc.* are presented in Table 2. Fresh rhizome pH ranged from 5.4–5.5, remaining acidic, with no significant effect from micronutrient treatments likely due to the acidic soil. TSS, which indicates sweetness quality in ginger, ranged from 3.53% to 5.5%, with the highest TSS in boron-treated samples (T4, 5.5%) due to role of boron in sugar translocation. Crude fibre content, an important dietary component, varied significantly across treatments from 4.10% to 5.18%, with the maximum in T7 (RDF+Zn+S) at 5.18%, highlighting the benefits of combined nutrient applications. Similar result on fibre content for this variety was reported by Sanwal *et al.* (2012).

Protein content, essential for health, reached a peak of 16.08% in T7 (RDF+Zn+S), followed by T10 (RDF+IISR micronutrient mixture), with the lowest in T1 (3.84%). Phenolic content, known for antioxidant properties, varied between 7.10 and 20.24 mg/100g, with the highest in T6 (Zn+B), indicating significant variation among treatments. Most of the quality parameters were found to be higher in secondary and micronutrient treatments alone or in combinations as these nutrients function in enzymes system and production of various primary or secondary metabolites.

Table 2. Rhizome yield and quality attributes of ginger as influenced by secondary and micronutrients

No.	Treatment	Fresh biomass yield (t/ha)	Rhizome yield (t/ha)	pH	TSS (%)	Crude fibre (%)	Crude protein (%)	Phenol (mg/100g)
T_1	FYM (Farm yard manure @15t/ha)	29.3	11.6	5.6	3.53	4.10	3.84	10.84
T_2	RDF (Recommend dose of fertilizer) 125:100:100 ($N - P_2O_5 - K_2O$ kg/ha)	26.1	8.5	5.6	3.53	4.21	4.37	7.10
T_3	RDF + Zn (2.5 kg/ha)	29.5	9.3	5.5	4.67	4.60	10.57	10.77
T_4	RDF + B (1 kg/ha)	30.6	9.9	5.6	5.50	4.13	6.56	17.08
T_5	RDF + S (15 kg/ha)	30.7	10.2	5.5	4.63	4.63	8.93	17.29
T_6	RDF + Zn @ 2.5 kg/ha + B @ 1 kg/ha	32.5	12.9	5.4	5.20	4.93	8.02	20.24
T_7	RDF + Zn @ 2.5 kg/ha + S @ 15 kg/ha	30.7	14.3	5.4	4.73	5.18	16.08	15.03
T_8	RDF + B @ 1 kg/ha + S @ 15 kg/ha	31.5	10.6	5.6	4.76	4.80	5.89	17.83
T_9	RDF + B @ 1 kg/ha + Zn @ 2.5 kg/ha + S @ 15 kg/ha	29.8	10.7	5.6	4.56	4.98	7.20	14.26
T_{10}	RDF + IISR micronutrient mixture (power G) 5 g/l at 60 and 90 days after germination	31.5	13.5	5.5	4.33	4.76	11.81	10.08
	SE. m (±)	0.70	1.14	0.089	0.37	0.22	0.737	0.407
	CD (P=0.05)	2.11	3.42	NS	1.11	0.66	2.20	1.22

Influence of S, B and Zn on the nutrient content of ginger rhizome

The concentration of N, P, K, Ca, Mg, and S in rhizome varied from 0.61 to 1.89, 0.15 to 0.22, 1.47 to 2.16, 0.19 to 0.61, 0.04 to 0.10 and 0.10 to 0.14%, respectively and the concentration of micro nutrients like B, Fe and Zn in the rhizomes of ginger was varied from 26.67 to 39.59, 129.4 to 469.1 and 18.1 to 33.5 mg/kg, respectively.

Concentration of N, K, Ca and Fe content in rhizome was found to be influenced by secondary and micronutrients supplementation. Highest N % in Zn+S treatment, K in Zn treatment, Fe, Ca concentration in sulphur treatment were noticed.

Influence of S, B and Zn on plant nutrient concentration at 135 DAP

The concentration of major nutrients like P, K and of plant tissue (%) varied from 0.09 to 0.14, 1.47 to 2.16 and 0.12 to 0.22, respectively and the concentration (ppm) of micro nutrients like

Fe, Cu, Mn and Zn varied from 19.0 to 311.0, 0.46 to 21.67, 252.2 to 487.03 and 26.06 to 56.23, respectively.

Nutrient uptake

Nitrogen uptake by rhizomes ranged from 11.9 to 50.9 kg/ha, with the highest in T7 (RDF+Zn+S) and generally higher under FYM and organic treatments compared to inorganic. Inclusion of secondary and micronutrient significantly boosted nitrogen uptake over RDF alone. Phosphorus, potassium, and sulphur uptake ranged from 2.9-6.2, 33.4-50.0, and 1.6-3.4 kg/ha, respectively, while iron, zinc, and boron uptake ranged from 348.6-1194.2, 35.8-79.2, and 40.9-84.2 g/ha, respectively with highest boron in T6 (RDF+Zn+B). Nutrient uptake followed the order K>N>P>S>Fe>B>Zn. Since the soils of Pottangi are deficient in S, B and Zn, application of zinc and sulphur either to soil or as foliar spray increases the nitrogen uptake due to balanced nutrition.

Plant nutrient uptake ranged from 8.6-13.16 kg/ha for P, 127.4-192.4 kg/ha for K, and 1.0-20.2 kg/ha for S, with the highest P and S uptake in T5 (RDF+S). B and Zn uptake were highest in T10 (IISR foliar spray), foliar application of micronutrients mixture. Total phosphorus uptake in ginger ranged from 13.6 to 18.4 kg/ha, highest in T7 and T8, combination of RDF with Zn and S and with B and S. Potassium uptake varied from 160.8 to 233.7 kg/ha, and sulphur uptake from 12.7 to 22.7 kg/ha, with the highest in T5 (RDF+S). Similar findings on uptake of potassium (213.31 kg/ha) was also reported by Prasad *et al.* (1997). Highest B and Zn uptake was also noticed in T10. Total uptake followed the order K>S>P>Fe>B>Zn. Total nutrient uptake by ginger rhizome and plant are presented in Table 3.

Rhizome yield was found to be positively and significantly correlated with N, P, S, Zn and B uptake as evident from the correlation coefficient values in Table 5. From regression equation it was observed that nutrients N, P, K, S, Fe, Zn, B together contributed 98 % variation in yield.

Table 3. Effect of S, B and Zn on the total nutrient uptake by ginger plant

No.	Treatment	P	K	S	Fe	Zn	B
			kg/ha			g/ha	
T_1	FYM (Farm yard manure @15t/ha)	15.1	160.8	16.2	1801.9	476.8	946.8
T_2	RDF (Recommend dose of fertilizer) 125:100:100 (N – P_2O_5 – K_2O kg/ha)	13.8	188.9	12.7	1970.4	334.2	587.4
T_3	RDF + Zn (2.5 kg/ha)	13.0	231.7	18.5	1138.4	542.8	924.6
T_4	RDF + B (1 kg/ha)	13.7	233.7	15.9	2818.1	435.2	1000.7
T_5	RDF + S (15 kg/ha)	16.4	207.2	22.7	1428.3	375.5	724.0
T_6	RDF + Zn @ 2.5 kg/ha + B @ 1 kg/ha	13.8	191.7	18.2	884.9	548.3	956.8
T_7	RDF + Zn @ 2.5 kg/ha + S @ 15 kg/ha	17.8	213.1	20.9	4063.3	396.2	853.5
T_8	RDF + B @ 1 kg/ha + S @ 15 kg/ha	17.8	192.6	20.8	2379.4	441.8	1002.9
T_9	RDF + B @ 1 kg/ha + Zn @ 2.5 kg/ha + S @ 15 kg/ha	13.6	167.1	21.3	757.4	300.1	858.7
T_{10}	RDF + IISR micronutrient mixture (power G) 5 g/l at 60 and 90 days after germination	18.4	199.0	14.5	532.0	945.3	1015.6

Post harvest soil status

Post harvest soil status *viz.*, effect of S, B and Zn on basic chemical properties, major nutrient and micronutrients of post harvest soil are presented in Table 4.

The initial soil pH, EC, and OC were 4.65, 0.098 dS/m, and 7.1 g/kg, respectively. After harvest, soil pH increased, which ranged between 4.6 and 5.2, while soluble salts and organic carbon content increased in all the treatments.

Post-harvest soil analysis revealed improved nutrient levels, especially for available P (34.77– 55.90 kg/ha, highest in FYM treatment) and S (11.25–34.79 mg/kg, highest in T5 with RDF+S). Increased P and S levels were noted

Table 4. Effect of S, B and Zn on basic chemical properties, major and micronutrients of post harvest soil

	Treatment	pH (1:2.5)	EC (dS/m)	OC (g/kg)	Av. P_2O_5 (kg/ha)	Av. S (mg/kg)	Fe (ppm)	Mn (ppm)	Zn (ppm)	B (ppm)
T_1	FYM (Farm yard manure @15t/ha)	4.7	0.11	13.3	55.90	12.17	124.76	168.73	1.71	0.70
T_2	RDF (Recommend dose of fertilizer) 125:100:100 (N – P_2O_5 – K_2O kg/ha)	4.6	0.23	11.1	52.94	22.12	121.72	158.70	1.59	0.59
T_3	RDF + Zn (2.5 kg/ha)	4.8	0.16	11.0	54.38	31.84	119.06	155.66	2.68	0.51
T_4	RDF + B (1 kg/ha)	4.7	0.12	12.1	54.52	11.25	119.38	157.06	1.95	0.97
T_5	RDF + S (15 kg/ha)	4.9	0.21	12	45.41	34.79	112.86	158.80	1.65	0.78
T_6	RDF + Zn @ 2.5 kg/ha + B @ 1 kg/ha	5.0	0.13	7.3	47.49	13.15	109.14	152.16	2.95	1.55
T_7	RDF + Zn @ 2.5 kg/ha + S @ 15 kg/ha	4.9	0.19	13.1	34.77	30.43	110.08	143.40	3.27	0.71
T_8	RDF + B @ 1 kg/ha + S @ 15 kg/ha	5.0	0.11	12.1	53.13	15.46	110.62	129.73	0.84	0.93
T_9	RDF + B @ 1 kg/ha + Zn @ 2.5 kg/ha + S @ 15 kg/ha	5.2	0.19	14.2	48.12	23.73	114.74	113.46	1.67	0.59
T_{10}	RDF + IISR micronutrient mixture (power G) 5 g/l at 60 and 90 days after germination	5.1	0.15	14.0	41.70	15.46	121.72	125.46	10.68	0.90
	SE. m (±)	0.23	0.039	0.05	2.74	5.05	8.68	15.42	0.75	0.104
	CD (P=0.05)	NS	NS	1.5	8.23	15.11	NS	NS	2.26	0.311

Table 5. Correlation matrix

	Yield	N	P	K	S	Fe	Zn	B
Yield	1.00							
N uptake	0.80*	1.00						
P uptake	0.90*	0.81*	1.00					
K uptake	0.63	0.89*	0.64	1.00				
S uptake	0.80	0.87*	0.78	0.73	1.00			
Fe uptake	0.34	0.36	0.51	0.26	0.45	1.00		
Zn uptake	0.86*	0.72	0.71	0.43	0.77	0.36	1.00	
B uptake	0.79	0.45	0.69	0.40	0.61	0.42	0.55	1.00

Regression equation

	Equation	R^2
Rhizome yield	Y=2.08+0.011N+0.75P*+0.03K-0.62S-0.011Fe+0.046Zn*+0.05B*	0.98
	Y= 2.21+0.73S*- 0.00Fe*+ 0.053Zn*+0.062B*	0.89

after meeting crop requirements, likely from residual treatment effects. Soil micronutrient status also improved in treatments with secondary and micronutrients, while a decrease was observed in RDF alone. The highest DTPA Zn was in T7 (RDF+Zn+S), followed by T6 (RDF + Zn + B) and T3 (RDF + Zn). Treatments receiving Zn and B applications significantly boosted Zn and B content in post-harvest soil levels after meeting crop requirements. Considerable change in the soil micronutrients status was observed in post-harvest soil over the initial status due to treatment effect as well as crop uptake.

Correlation and regression

Rhizome yield was found to be positively and significantly correlated with N, P, S, Zn and B uptake as evident from the correlation coefficient values in Table 5.

Conclusion

The Eastern Ghat Highland agroclimatic zone, particularly Koraput and Nabarangpur, is suited for ginger cultivation due to its warm, humid climate and high altitude (900–1400 m amsl). However, ginger productivity is low due to traditional practices with improper and imbalanced nutrients input used by tribal farmers. Improved growth, yield, and quality attributes were observed with secondary and micronutrient applications, enhancing tiller numbers, rhizome spread, and nutritional quality. The highest responses were observed in micronutrient combinations Zn+S treatments and multi micronutrient foliar applications, demonstrating that balanced nutrient management can significantly boost quality ginger productivity and support tribal livelihoods in this region.

Future research needs

Fortified micronutrients with organic or nano fertilizers to supplement deficient nutrients and maintain soil health by balancing nutrients. Effect of liming should be included in the treatment as most of the soils are acidic in nature in that region which might be affecting the rhizome which is grown underground.

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