



RESEARCH ARTICLE

Precision farming for optimised nutrient use efficiency and yield of *Capsicum annuum* L. in southern coastal plain of Kerala

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Abstract

Modern agriculture has driven significant yield increase but also led to widespread chemical fertiliser use, causing soil health deterioration and multiple nutrient deficiencies. In India, studies evaluating optimal nutrient management strategies for high-value crops like chilli in nutrient-deficient sandy coastal soils using precision farming techniques are limited. To address this knowledge gap, a field experiment was conducted in nutrient-deficient sandy coastal soils of Kerala during 2023–2024 using a split plot design to evaluate balanced nutrition strategies combining fertigation and foliar application of nutrients in *Capsicum annuum* L. For that, 75, 100 and 125 % of 210:46:276 nitrogen, phosphorus and potassium (NPK) kg ha⁻¹, were applied through fertigation and were indicated as F₁, F₂ and F₃ respectively. It was compared against fertigation dosage of 75:40:25 NPK kg ha⁻¹ (F₄). Secondary and micronutrient effects were studied using soil application of sulphur (25 kg ha⁻¹) S₁, foliar nutrition of 0.5 % Sampoorina (S₂), foliar nutrition of 0.25 % (S₃) and 0.5 % (S₄) of customised multinutrient mixtures with water spray (S₅) as control. Results demonstrated that the treatment F₃S₂ recorded maximum fruit weight (8.2 g) and total nutrient uptake of potassium (312.12 kg ha⁻¹), sulphur (37.19 kg ha⁻¹) and zinc (434.02 g ha⁻¹), while F₂S₂ exhibited highest uptake of calcium (128.04 kg ha⁻¹) and iron (15.74 kg ha⁻¹). Maximum magnesium uptake (111.99 kg ha⁻¹) was observed in F₃S₄ substantially outperforming F₄S₅. Hence, 263:60:345 NPK kg ha⁻¹ with foliar nutrition of Sampoorina optimised balanced nutrition and productivity of chilli in sandy coastal soils.

Keywords: chilli; drip irrigation; fertigation; foliar spray; micronutrient; nutrient uptake

Introduction

Intensive agriculture has played a pivotal role in the success of the Green Revolution; however, it has also led to the widespread and often indiscriminate use of chemical fertilisers and pesticides, with primary emphasis on maximising crop yields. The unbalanced and continuous application of chemical fertilisers in intensive cropping systems has resulted in the deterioration of soil health, emergence of multi-nutrient deficiencies, reduced productivity, poor produce quality and increased environmental hazards (1). Over the decades, the number of nutrient-deficient elements in Indian soils has expanded dramatically from nitrogen alone in 1950 to nine critical nutrients (N, P, K, S, B, Cu, Fe, Mn and Zn) by 2005–2006 (2). Indiscriminate use of NPK fertilisers has further aggravated micronutrient deficiencies, with zinc deficiency being the most widespread, followed by sulphur, iron, copper, manganese and boron (3).

Kerala, along with Rajasthan, Andhra Pradesh, Odisha and Madhya Pradesh, accounts for the highest share of annual soil degradation costs in India (4). Kerala's soils face multiple constraints, including erosion, salinity, acidification, waterlogging, low organic carbon, excess phosphorus and deficiencies of magnesium and boron (5, 6). The National Bureau of Soil Survey and Land Use

Planning (NBSS & LUP) has classified the state into 23 agro-ecological units, five of which lie in the coastal zone and exhibit unique soil and hydrological characteristics (6). Among these, five AEUs are located in the coastal zone and are characterised by unique soil and hydrological conditions.

The southern coastal plain (AEU 1) represents predominantly coastal areas with sandy soils characterised by light texture, poor nutrient status, low cation exchange capacity (CEC), minimal soil organic matter and reduced microbial activity, along with widespread deficiencies of zinc, iron and boron. These soils also exhibit low water-holding capacity and diminished fertility, rendering them largely unsuitable for many crops and posing significant management challenges for farmers.

Fertigation, a key component of precision farming, involves the application of fertilisers through the irrigation system and has proven to be an efficient approach for synchronised nutrient and water management. This technique enables precise fertiliser application, reduces nutrient losses through leaching, ensures uniform distribution of nutrients within the active root zone and enhances crop productivity (5). Consequently, fertigation can be considered a viable nutrient management strategy for sandy soils, particularly for primary nutrients with high crop demand.

Although secondary and micronutrient requirements are comparatively low, they are essential for achieving optimal crop growth and productivity. Fertigation of these nutrients is constrained by factors such as low crop requirement, fertiliser purity, solubility issues and nutrient incompatibility. Therefore, these nutrients are often applied through soil or foliar methods. Foliar application, however, is an effective alternative to overcome fixation losses associated with soil application and allows for faster and more economical nutrient uptake and assimilation (7).

Chilli (*Capsicum annuum* L.), a widely consumed spice crop with high domestic and international demand, is a nutrient-exhaustive crop. Standardisation of integrated nutrient management practices for such high-value crops is imperative, particularly in sandy soils with inherently low fertility. Fertigation offers a promising solution; however, a substantial knowledge gap exists regarding nutrient management through fertigation in these soils. Therefore, the present study was undertaken to optimise nutrient management under open precision farming conditions in AEU 1.

Materials and Methods

The study was conducted at a farmer's field in the southern coastal plain (AEU 1) of Alappuzha district, Kerala, India during the period from November 2023 to April 2024 by cultivating hybrid variety Sierra. The geographic coordinates of study area were 09°45.493' N, 76°17.468' E, having an elevation of 46 m above mean sea level recorded using a Garmin Etrex 32X GPS. During the growing period, the ambient temperature ranged from 16.1 to 39.1 °C with daily evaporation rates varying between 0.8 and 8.5 mm.

Soil samples from each treatment were collected for analysis. Subsequently, the samples were air-dried and finely pulverised. Samples were subjected to sieving using a 2 mm mesh. Coarse fractions above 2 mm were eliminated. Fine earth fractions were contained in plastic jars and systematically organised on sample racks for laboratory analysis. Soil samples were collected from a depth of 15 cm. The physical and chemical properties of the experimental area was provided in Table 1.

The general nutrient recommendation for chilli through fertigation advocated by Kerala Agricultural University (KAU) is 210:48:276 NPK kg ha⁻¹ (19). In conventional nutrient management, where soil application of nutrients follows a lower NPK dosage of 75:40:25 kg ha⁻¹ (20). Since the fertigation practice demands higher primary nutrient requirements, there is a necessity for standardisation of fertigation especially in sandy soils having poor nutrient retention capacity.

The effects of secondary and micronutrients on the growth of chilli were also assessed through the application of multinutrient formulations. Sampoorana, a customised fertiliser is a multinutrient mixture formulated by KAU, is an effective proven nutrient augmentor in vegetables. The composition of Sampoorana is Zn-4.2 %, B-3.0 %, Cu-0.4 %, Fe-0.15 %, Mn-0.14 % and Mo-0.015 %. A multinutrient mixture for chilli was also formulated in the study based on general nutrient content of plant. The composition of mixture was MgSO₄·7H₂O (5 %), ZnSO₄·7H₂O (0.1 %) and borax (0.1 %).

The experiment followed a split-plot design with four main-plot treatments and five sub-plot treatments, replicated three times, resulting in a total of 60 treatment combinations. The main plot experiments were designed to study the effect of different graded dosages of primary nutrients whereas the sub plot treatments laid out for studying the influence of secondary and micronutrients on growth attributes of chilli.

The main-plot treatments were as follows: F₁- 158:36:207 kg N:P:K ha⁻¹ (75 % of F₂), F₂- 210:48:276 kg N:P:K ha⁻¹ (100 % of KAU Adhoc precision farming recommendation, 2013), F₃- 263:60:345 kg N:P:K ha⁻¹ (125 % of F₂) and F₄- 75:40:25 kg N:P:K ha⁻¹ (KAU conventional recommendation, KAU 2016). The sub-plot treatments included: S₁- Soil test-based recommendation of secondary and micronutrients, with sulphur applied at 25 kg ha⁻¹ based on soil deficiency (20); S₂- Foliar application of Sampoorana (KAU multi mix for vegetables, 0.5 %); S₃- Foliar application of customised multinutrient mixture (0.25 %); S₄- Foliar application of customised multinutrient mixture (0.5 %); and S₅- Water spray as control. Fertigation was applied in 40 splits at three-day intervals, while foliar applications were carried out at 15, 30 and 45 days after

Table 1. Physico-chemical composition of soil of the experimental field

Characters	Value	Rating	Methodology
Mechanical composition			
Sand (%)	60.13	Sandy clay loam	Bouyoucos hydrometer method (8)
Silt (%)	9.35		
Clay (%)	30.52		
Physical property			
Bulk density (g cm ⁻³)	1.53		Core method (9)
Chemical properties			
pH	7.03	Neutral	Soil water suspension of 1:2.5 and read in pH meter (10)
EC, dS m ⁻¹	0.18	Normal	Soil water suspension of 1:2.5 and read in Electrical conductivity meter (10)
Organic carbon %	0.34	Low	Titration method (11)
Available N, kg ha ⁻¹	290.11	Medium	Alkaline permanganate method (12)
Available P, kg ha ⁻¹	28.37	High	Olsen's method (13)
Available K, kg ha ⁻¹	134.18	Medium	Neutral ammonium acetate extract using Flame photometer (10)
Available Ca, mg kg ⁻¹	630.67	Sufficient	Neutral ammonium acetate extract using Flame photometer (10)
Available Mg, mg kg ⁻¹	184.61	Sufficient	Neutral ammonium acetate extract using Atomic absorption spectrophotometer (14)
Available S, mg kg ⁻¹	2.50	Deficient	CaCl ₂ extraction using spectrophotometer (15, 16)
Available Fe, mg kg ⁻¹	60.10	Sufficient	DTPA extract method using Atomic absorption spectrophotometer (17)
Available Mn, mg kg ⁻¹	2.10	Sufficient	DTPA extract method using Atomic absorption spectrophotometer (17)
Available Zn, mg kg ⁻¹	1.08	Sufficient	DTPA extract method using Atomic absorption spectrophotometer (17)
Available Cu, mg kg ⁻¹	2.25	Sufficient	DTPA extract method using Atomic absorption spectrophotometer (17)
Available B, mg kg ⁻¹	0.51	Sufficient	Hot water soluble extraction (18)

EC: electrical conductivity; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulphur; Fe: iron; Mn: manganese; Zn: zinc; Cu: copper; B: boron.

transplanting (DAT). All the agricultural operations were followed as per recommended package and practices (20). Statistical analysis was performed at 5 % significance level (21). Four plants on average per experimental unit were used to measure the following attribute.

Fruit weight (g)

The chilli fruits at each picking were mixed. From the pooled sample, hundred fruits were drawn randomly and their weight was recorded and expressed in grams.

Yield per plant

Total fruit yield from each tagged plant was found out and mean yield was calculated in kg per plant.

Agronomic efficiency and total nutrient uptake of nutrients were recorded after the harvest.

Agronomic efficiency

AE =

Yield in fertilised plot (kg ha⁻¹) - Yield in control plot (kg ha⁻¹)

Amount of nutrients applied (kg ha⁻¹)

Total uptake of N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu and B by crop at harvest

Nutrients N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu and B were measured by plant analysis using standard procedures and uptake was calculated by multiplying the nutrient content with dry matter yield of respective treatment and expressed as kg ha⁻¹ and g ha⁻¹. Methods of analysis for each plant sample nutrient are shown in Table 2.

Table 2. Methods used for analysis of plant samples

Nutrient	Digestion procedure	Method of estimation
N	H ₂ SO ₄ digestion	Distillation and titration (10)
P	9:4 HNO ₃ -HClO ₄ diacid digestion	Vanado molybdate yellow colour method using spectrophotometer (9)
K	9:4 HNO ₃ -HClO ₄ diacid digestion	Direct reading using flame photometer (10)
Ca	9:4 HNO ₃ -HClO ₄ diacid digestion	Direct reading using flame photometer (10)
Mg	9:4 HNO ₃ -HClO ₄ diacid digestion	Direct reading using atomic absorption spectrophotometer (22)
S	9:4 HNO ₃ -HClO ₄ diacid digestion	Turbidimetry method using spectrophotometer (23)
Fe, Zn, Mn, Cu	9:4 HNO ₃ -HClO ₄ diacid digestion	Direct reading using Atomic absorption spectrophotometer (22)
B	9:4 HNO ₃ -HClO ₄ diacid digestion	Azomethine -H colorimetric method (24)

N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulphur; Fe: iron; Mn: manganese; Zn: zinc; Cu: copper; B: boron.

Results

Fruit weight (g)

Current findings showed that different levels of primary and levels of secondary and micronutrients had a significant effect on fruit weight (Table 3). Among the primary nutrient treatments, the highest fruit weight was recorded with F₃ (7.42 g), which was statistically similar with F₂ (7.05 g) and the tool for comparison used was ANOVA (F test). The lowest fruit weight was observed with F₄ (5.54 g). In the subplot treatments, the maximum fruit weight was recorded with a 0.5 % S₄ (7.01 g), which was performing similar with S₂ (6.95 g) and S₃ (6.74 g). The minimum fruit weight was observed with the S₅ treatment (5.98 g). For interaction effects, the highest fruit weight (8.20 g) was recorded in the combination of F₃ with a S₂, while the lowest fruit weight (5.76 g) was observed with F₄ combined with S₅.

Table 3. Effect of multinutrients on yield parameters

Treatments		
Levels of primary nutrients(F)		
	Fruit weight(g)	Yield per plant (kg)
F ₁ -75 % KAU Adhoc NPK	6.48 ^b	1.65 ^b
F ₂ -100 % KAU Adhoc NPK	7.05 ^a	1.90 ^a
F ₃ -125 % KAU Adhoc NPK	7.42 ^a	2.01 ^a
F ₄ -100 % KAU POP NPK	5.54 ^c	1.31 ^c
SEm (±)	0.143	0.047
CD (0.05 %)	0.493	0.154
Levels of secondary and micronutrients (S)		
S ₁ -soil test based multinutrient application	6.45 ^b	1.64 ^c
S ₂ -0.5 % Sampoorna KAU multimix	6.95 ^a	1.88 ^{ab}
S ₃ -0.25 % multinutrient mixture	6.74 ^{ab}	1.76 ^{bc}
S ₄ -0.5 % multinutrient mixture	7.01 ^a	1.90 ^a
S ₅ -water spray	5.98 ^c	1.40 ^d
SEm (±)	0.115	0.045
CD (0.05 %)	0.335	0.124
Interactions (F × S)		
F ₁ S ₁	6.63	1.70
F ₁ S ₂	6.83	1.83
F ₁ S ₃	6.79	1.71
F ₁ S ₄	6.55	1.74
F ₁ S ₅	5.63	1.29
F ₂ S ₁	7.13	1.84
F ₂ S ₂	7.10	2.01
F ₂ S ₃	7.30	1.97
F ₂ S ₄	7.37	2.07
F ₂ S ₅	6.36	1.61
F ₃ S ₁	7.40	1.92
F ₃ S ₂	8.20	2.25
F ₃ S ₃	7.23	2.02
F ₃ S ₄	8.13	2.26
F ₃ S ₅	6.16	1.58
F ₄ S ₁	4.63	1.11
F ₄ S ₂	5.66	1.45
F ₄ S ₃	5.63	1.36
F ₄ S ₄	6.00	1.52
F ₄ S ₅	5.76	1.13
SEm (±)	0.231	0.087
CD (0.05 %)	0.663	NS

KAU: Kerala Agricultural University; POP: package of practice recommendations; N: nitrogen; P: phosphorus; K: potassium; NS: not significant.

Yield per plant (kg)

The data pertaining to yield per plant is furnished in Table 3 and was revealed that F₃ (2.01 kg) recorded maximum yield per plant which was on par with F₂ (1.90 kg) and minimum for F₄ (1.31 kg). For subplot treatment maximum value recorded for S₄ (1.90 kg), which was comparable with S₂ (1.88 kg) and minimum for S₅ (1.40 kg) and interaction found to be non-significant.

Agronomic efficiency (kg kg⁻¹)

The agronomic efficiency of primary nutrients in Table 4 revealed no significant difference in the main plot for nitrogen and phosphorus; however, for potassium, F₃ exhibited the highest agronomic efficiency (93.00 kg kg⁻¹), comparable to F₂ (78.99 kg kg⁻¹). In the subplot treatment, the soil application of sulphur exhibited the highest agronomic efficiency for nitrogen (95.22 kg kg⁻¹), phosphorus

(19.21 kg kg⁻¹) and potassium (95.11 kg kg⁻¹), whereas the S₅ had the lowest efficiency (51.06, 9.83 and 52.97 kg kg⁻¹). The interaction among the treatments was not significant.

Table 4. Agronomic efficiency influenced by levels of nutrients

Treatments	Agronomic efficiency (kg kg ⁻¹)		
Levels of primary nutrients (F)			
	Nitrogen	Phosphorus	Potassium
F ₁ -75 % KAU Adhoc NPK	61.95	15.71	47.14 ^b
F ₂ -100 % KAU Adhoc NPK	77.86	14.81	78.99 ^a
F ₃ -125 % KAU Adhoc NPK	73.30	11.16	93.00 ^a
F ₄ -100 % KAU POP NPK	0	0	0
SEm (±)	4.957	1.214	4.220
CD (0.05 %)	NS	NS	16.582
Levels of secondary and micronutrients (S)			
S ₁ - soil test-based multinutrient application	95.22	19.21	95.11 ^a
S ₂ -0.5 % Sampoorna KAU multimix	75.31	14.66	77.92 ^{ab}
S ₃ -0.25 % multimix nutrient mixture	70.63	13.93	71.97 ^{ab}
S ₄ -0.5 % multimix nutrient mixture	63.03	11.82	67.23 ^b
S ₅ -water spray	51.06	9.83	52.97 ^b
SEm (±)	9.066	1.992	8.697
CD (0.05 %)	15.700	5.815	25.381
Interactions (F × S)			
F ₁ S ₁	103.55	26.26	78.79
F ₁ S ₂	66.96	16.98	50.94
F ₁ S ₃	64.80	16.43	49.31
F ₁ S ₄	38.85	9.85	29.56
F ₁ S ₅	35.59	9.08	27.08
F ₂ S ₁	96.18	18.29	97.58
F ₂ S ₂	73.96	14.06	75.03
F ₂ S ₃	78.57	14.94	79.71
F ₂ S ₄	72.46	13.78	73.51
F ₂ S ₅	68.14	12.96	69.13
F ₃ S ₁	85.92	13.07	108.96
F ₃ S ₂	85.00	12.93	107.80
F ₃ S ₃	68.53	10.42	86.91
F ₃ S ₄	77.77	11.83	98.63
F ₃ S ₅	49.45	7.52	62.71
SEm (±)	15.700	3.450	15.063
CD (0.05 %)	NS	NS	NS

KAU: Kerala Agricultural University; POP: package of practice recommendations; N: nitrogen; P: phosphorus; K: potassium; NS: not significant.

Total nutrient uptake of nutrients

From Table 5, it was found that among primary nutrients maximum uptake of nitrogen, potassium (Fig. 1), sulphur, iron, boron, phosphorus, magnesium (Fig. 2), manganese, zinc (Fig. 3) and copper were recorded for F₃. In the secondary and micronutrient levels Sampoorna foliar spray exhibited highest nutrient uptake for nitrogen, phosphorus, calcium, iron, manganese, zinc, copper and boron whereas foliar application of S₄ resulted in the highest uptake of potassium, magnesium and sulphur.

Discussion

Balanced nutrition is essential for enhancing plant growth, yield and quality. The increased yield attributes and yield observed in the present study may be attributed to enhanced source capacity and sink strength resulting from uninterrupted nutrient availability at optimum doses. Foliar application of micronutrients proved superior to soil application, as foliar sprays rapidly corrected nutrient deficiencies, bypassed nutrient fixation and leaching losses in the soil and thereby improved nutrient use efficiency (25).

Fertigation treatments significantly improved nutrient use efficiency in chilli. Agronomic efficiency of potassium was highest under F₃, while nitrogen and phosphorus efficiencies did not differ significantly, likely due to favourable nutrient water interactions within the root zone even at lower fertigation levels, as reported in several vegetable crops (26–28). The enhanced efficiency can be attributed to dropwise water application, which maintains optimum moisture in the active root zone and minimises leaching losses. Unlike surface irrigation, where mass water flow rapidly transports NO₃-N to deeper soil layers (29), fertigation maintains higher NO₃-N concentrations at shallow depths, improving nutrient availability (30). For phosphorus, which tends to undergo fixation and accumulate in upper soil layers, fertigation improves mobility and availability within the root zone compared to conventional soil application (31, 32). Similarly, potassium fertigation in multiple splits ensures efficient uptake and reduces leaching losses in sandy soils with high K mobility (33, 34).

Secondary and micronutrient application significantly influenced nutrient use efficiency. Soil application of sulphur (S₁) recorded the highest agronomic efficiency for all major nutrients due to synergistic effects that enhanced nitrogen, phosphorus and potassium uptake. Application of secondary and micronutrients has been reported to improve macronutrient use efficiency (35) and increase apparent nutrient recoveries (36).

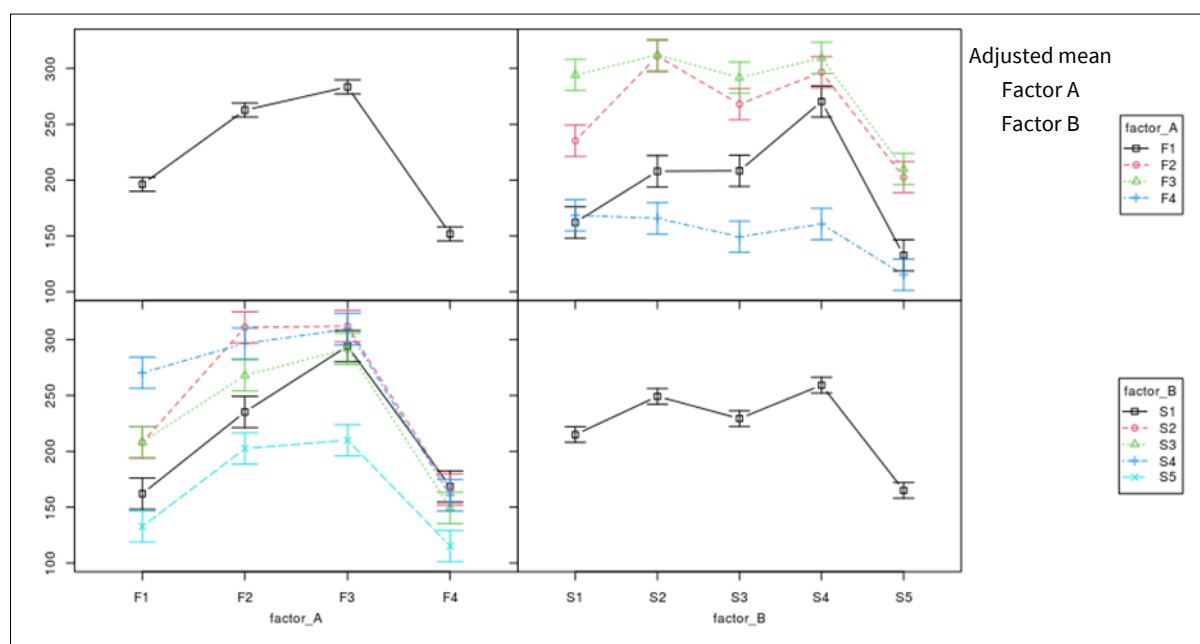
The highest nutrient uptake was recorded with F₃, except for calcium, though F₂ showed comparable uptake of nitrogen, potassium, sulphur, iron and boron. This improvement can be attributed to frequent nutrient supply through fertigation, which stimulates root activity, enhances nutrient availability in the root zone, reduces leaching losses and increases plant nutrient concentration (37, 38). Enhanced phosphorus uptake was associated with nitrogen-mediated mobilisation and synergistic effects that promoted root growth and physiological capacity for nutrient absorption (39–41). Increased potassium uptake was similarly linked to vigorous plant growth and synergistic nutrient interactions that strengthened absorption mechanisms.

Fertigation levels significantly influenced secondary nutrient content in chilli, with higher concentrations of calcium, magnesium and sulphur resulting from improved plant growth and robust root systems (42). Optimal calcium and zinc levels enhanced phosphorus and potassium uptake, magnesium showed favourable interactions with nitrogen and phosphorus and sulphur exhibited a strong positive relationship with nitrogen absorption (43). Micronutrient content and uptake (Fe, Mn, Zn, Cu and B) increased significantly with higher fertigation levels, with F₃ (263:60:345 NPK kg ha⁻¹) recording maximum values statistically comparable to F₂, corroborating findings in bitter melon (44). Synergistic relationships between potassium and micronutrients, along with overlapping physiological roles of boron and potassium, further enhanced nutrient uptake efficiency (45).

Table 5. Effect of multinutrients on total nutrient uptake of chilli

Treatments	Total uptake of nutrients							
	Nitrogen (kg ha ⁻¹)	Phosphorus (kg ha ⁻¹)	Calcium (kg ha ⁻¹)	Sulphur (kg ha ⁻¹)	Iron (kg ha ⁻¹)	Manganese (g ha ⁻¹)	Copper (g ha ⁻¹)	Boron (g ha ⁻¹)
Main plot								
F ₁	310.77 ^b	23.41 ^c	80.09 ^b	26.44 ^b	11.27 ^b	561.09 ^c	242.98 ^{bc}	142.24 ^b
F ₂	408.57 ^a	31.04 ^b	105.04 ^a	31.81 ^a	13.04 ^a	708.69 ^b	300.21 ^{ab}	175.88 ^a
F ₃	428.71 ^a	36.04 ^a	99.19 ^a	33.75 ^a	13.71 ^a	784.63 ^a	342.59 ^a	203.04 ^a
F ₄	207.42 ^c	16.94 ^d	64.58 ^c	22.17 ^c	9.61 ^c	449.50 ^d	182.32 ^c	108.73 ^c
SEm (±)	16.957	0.85	2.990	0.613	0.342	12.780	17.581	8.264
CD 0.05 %	58.688	2.972	10.376	2.124	1.184	44.233	60.834	28.593
Subplot								
S ₁	312.54 ^c	25.29 ^c	79.62 ^b	27.29 ^b	11.45 ^c	581.15 ^c	250.51 ^c	146.86 ^c
S ₂	407.43 ^a	32.27 ^a	100.21 ^a	31.23 ^a	13.20 ^a	761.21 ^a	325.89 ^a	191.64 ^a
S ₃	354.60 ^{bc}	27.86 ^{ab}	93.28 ^a	29.04 ^b	11.88 ^{bc}	645.92 ^{bc}	276.67 ^{bc}	156.67 ^{bc}
S ₄	378.99 ^{ab}	29.39 ^{bc}	97.92 ^a	31.79 ^a	12.70 ^{ab}	669.89 ^b	304.60 ^{ab}	176.73 ^{ab}
S ₅	240.77 ^d	19.52 ^d	65.09 ^c	23.33 ^c	10.30 ^d	471.72 ^d	177.45 ^d	115.47 ^d
SEm (±)	17.170	1.010	3.020	0.741	293.943	26.261	13.414	7.230
CD 0.05 %	49.463	2.934	8.722	2.145	846.744	75.664	36.630	20.841
Interactions (F × S)								
F ₁ S ₁	259.05	19.75	65.78	23.80	10.18	491.61	219.55	120.82
F ₁ S ₂	363.29	28.67	90.94	28.16	11.88	637.48	259.98	162.03
F ₁ S ₃	312.99	23.92	83.29	26.03	10.99	560.72	246.41	142.08
F ₁ S ₄	391.09	27.58	98.00	31.08	13.11	680.89	308.88	173.76
F ₁ S ₅	227.41	17.15	62.44	23.13	10.18	434.76	180.08	112.54
F ₂ S ₁	346.47	29.08	94.81	27.10	11.65	615.12	247.64	145.19
F ₂ S ₂	520.35	36.63	128.04	36.77	15.74	941.43	404.83	226.41
F ₂ S ₃	453.86	33.28	113.51	33.00	12.89	767.54	312.10	173.04
F ₂ S ₄	446.41	34.30	117.41	36.35	13.94	720.37	339.00	204.57
F ₂ S ₅	275.76	21.91	71.44	25.75	10.99	498.99	197.48	130.18
F ₃ S ₁	423.80	35.91	98.78	34.87	14.13	757.02	354.82	198.15
F ₃ S ₂	500.69	44.26	116.58	37.19	15.15	991.38	417.40	243.45
F ₃ S ₃	473.46	38.35	108.36	35.33	14.40	789.14	352.05	210.04
F ₃ S ₄	460.78	37.52	103.72	35.22	13.68	795.41	379.87	220.46
F ₃ S ₅	284.81	24.16	68.49	23.80	11.19	590.18	208.81	143.12
F ₄ S ₁	220.83	16.42	59.10	28.16	9.85	460.84	180.04	123.30
F ₄ S ₂	245.40	19.34	65.29	26.03	10.03	474.54	221.33	134.66
F ₄ S ₃	178.10	15.90	67.96	31.08	9.26	466.30	196.13	101.53
F ₄ S ₄	217.68	18.18	72.55	23.13	10.07	482.88	190.66	108.12
F ₄ S ₅	175.08	14.86	58.00	18.28	8.83	362.95	123.44	76.05
SEm (±)	34.341	2.030	6.050	1.487	0.587	52.542	26.820	14.471
CD 0.05 %	NS	NS	17.454	4.284	1.693	NS	NS	NS

NS: Not significant.

**Fig. 1.** Interaction of multinutrients on total potassium uptake of chilli.

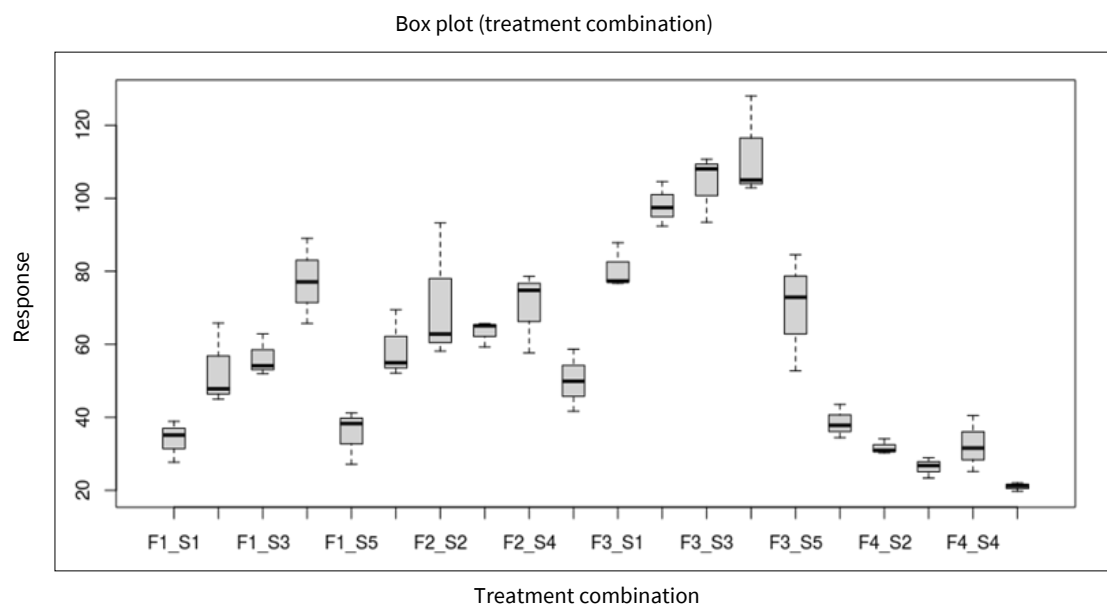


Fig. 2. Interaction of multinutrients on magnesium uptake in chilli.

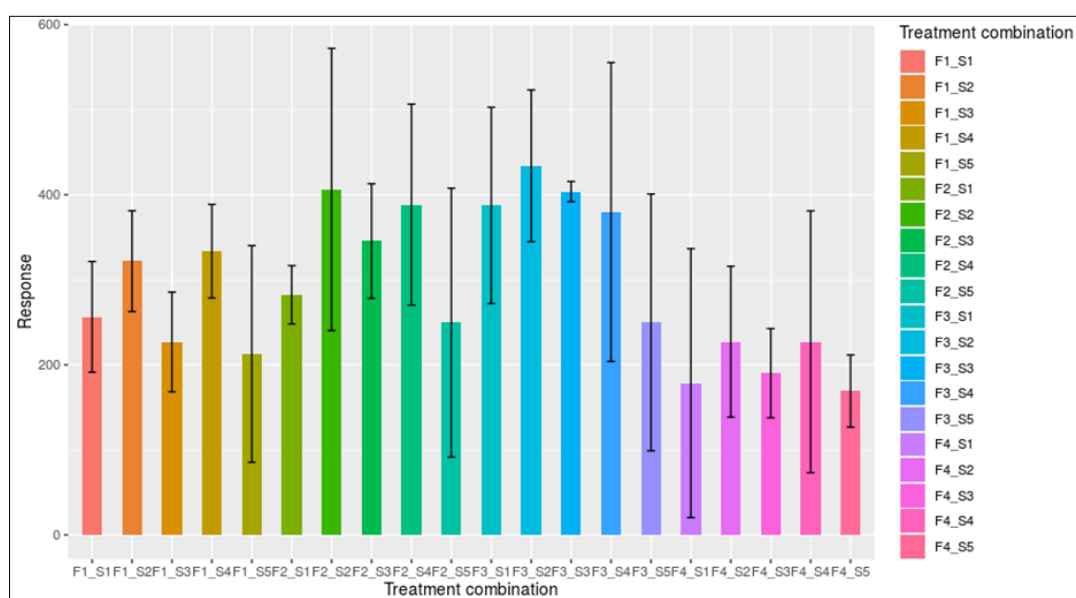


Fig. 3. Levels of nutrients on total zinc uptake of chilli.

Foliar application of secondary and micronutrients in combination with fertigation of primary nutrients significantly enhanced nutrient content and uptake in chilli. Foliar spray of Sampooma S₂ resulted in the highest uptake of nitrogen, phosphorus, calcium, iron, manganese, zinc, copper and boron, while S₄ recorded maximum uptake of potassium, magnesium and sulphur. Micronutrients enhanced macronutrient uptake by activating enzymes involved in key metabolic processes (46). Synergistic interactions were evident, with iron enhancing calcium uptake and zinc promoting sulphur absorption. Direct foliar application at critical growth stages increased micronutrient concentration in plant tissues, making foliar nutrition an efficient, economical and climate-resilient approach for improving fertiliser use efficiency, yield and quality (46, 47).

Interaction effects between fertigation and foliar nutrition revealed significant synergism in nutrient uptake. The combination F₃S₂ recorded the highest potassium uptake, F₂S₂ showed maximum calcium and iron uptake and F₃S₄ resulted in the highest magnesium uptake. Maximum sulphur and zinc uptake were also observed under F₃S₂, while interactions for nitrogen, phosphorus,

copper, manganese and boron were non-significant. These synergistic effects can be attributed to multinutrient supply supporting vital physiological processes such as protein synthesis, enzymatic activity, photosynthesis and respiration. Integrated fertigation and foliar nutrition enhanced the availability of both native and applied nutrients, resulting in higher yield and improved nutrient uptake, in agreement with findings in maize and other crops (48–50).

Conclusion

The results of this study demonstrated that the application of 263:60:345 NPK kg ha⁻¹ combined with a 0.5 % Sampooma foliar spray significantly enhanced yield, nutrient use efficiency and nutrient uptake in chilli grown on nutrient-deficient sandy soils. Based on these findings, this treatment is recommended for adoption in the southern coastal sandy plain (AEU 1). However, further studies across different chilli varieties and locations are required to validate the consistency of these results and to assess economic feasibility as well as long-term impacts on soil health and fruit yield.

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Authors' contributions

AD carried out the experiment and drafted the manuscript, with support from co-authors who assisted in supervising the project. AD also organised the article structure, ensured coherence between sections and critically analysed the data to present a comprehensive discussion. RVRN conceived and planned the experiments and made substantial revisions to enhance the scientific rigour, coherence and overall presentation of the manuscript, including strengthening and reorganising key sections. TV, PPG and RB contributed to the research design and implementation, data analysis and manuscript preparation. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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