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Bio-efficacy and phytotoxicity assessment of SVK DRIP bio-stimulant on okra (*Abelmoschus esculentus* L. Moench)

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Abstract

Aims: To evaluate the bio-efficacy, phytotoxic potential and yield impact of SVK DRIP bio-stimulant on okra hybrid Arka Nikita cultivated in southern transitional agro-climatic zones.

Methodology: A randomized complete block design (RCBD) field experiment with seven treatments replicated thrice was conducted from December 2023 to May 2024 at Zonal Agricultural and Horticultural Research Station (ZAHRS), KSNUAHS, Shivamogga, Karnataka (13°58′N, 75°34′E, 650 m altitude). Treatments included SVK DRIP at 0.50, 1.00, 1.50 and 2.00 L acre^{-1} applied as soil drench at 25 and 45 days after sowing (DAS), compared against untreated control and recommended fertilizer dose (RDF). Morphological parameters (plant height, leaf area, LAI) were recorded at 35, 55 and 75 DAS. Chlorophyll content was measured via DMSO extraction at corresponding intervals. Yield components were quantified over 26 harvests. Phytotoxicity was assessed on a 0-100 scale at 1, 3, 5- and 10-days post-application. Soil properties were analysed pre-and post-harvest. Data were subjected to ANOVA at P = 0.05.

Results: SVK DRIP at 2.00 L acre^{-1} (T_5) significantly enhanced plant height (82.0 cm), leaf area (4232 cm^2 plant^{-1}), LAI (1.176) and total chlorophyll (2.385 mg g^{-1} leaf fresh weight) at 75 DAS, representing 16.0%, 15.4%, 15.4% and 17.5% increases over control, respectively. Yield per hectare reached 12.78 t ha^{-1} at T5 versus 10.84 t ha^{-1} in control (17.9% gain). Fruit number increased by 16.3% (50 fruits plant^{-1} vs. 43 in control). No phytotoxic symptoms (0 rating on 0-100 scale) were observed across all treatments and observation intervals. Post-harvest soil analysis revealed efficient nutrient uptake (N: 15.7%, P: 20%, K: 5.0% reduction) without toxicity or micronutrient accumulation.

Conclusion: SVK DRIP bio-stimulant at optimized dose (2.00 L acre^{-1}) offers a safe, effective alternative for enhancing okra productivity through improved morphophysiological attributes and nutrient utilization, without phytotoxic or edaphic risks, aligning with sustainable agriculture paradigms in tropical and subtropical horticulture.

Keywords: Bio-stimulant, chlorophyll, growth parameters, okra, phytotoxicity, yield attribut

1. Introduction

Okra (*Abelmoschus esculentus* L. Moench), globally known as lady's finger, bhendi, or gumbo, is a warm-season annual vegetable originating from tropical Africa and extensively cultivated in Asia, particularly India, for its immature edible pods [1]. India remains the world's largest okra producer and consumer, with annual production surpassing 6 million tons, predominantly from Maharashtra, Gujarat, Karnataka and Andhra Pradesh [2]. The crop's demand is driven by nutritional richness (vitamins A, B, C; minerals; dietary fiber) and medicinal properties, making it economically significant for smallholder farmers in semi-arid regions.

Intensive agriculture's reliance on synthetic fertilizers has paradoxically diminished soil quality despite yield gains. Excessive inorganic nitrogen application accelerates soil acidification, depletes organic matter, disrupts nutrient cycling and reduces crop nutritional density [3]. Prolonged fertilizer dependency results in 20-30% nutrient use inefficiency, with major nutrient losses via leaching, runoff and fixation, thereby elevating production costs and environmental footprints [4]. In developing economies, fertilizer-price inflation significantly burdens resource-limited farmers, necessitating cost-effective alternatives that sustain productivity while preserving soil health.

Bio-stimulants-naturally derived organic extracts rich in plant growth regulators (auxins, cytokinins, gibberellins), amino acids, vitamins and trace elements-have emerged as promising solutions [5]. These bioactive compounds enhance nutrient bioavailability, stimulate root development, strengthen photosynthetic machinery and fortify stress-tolerance mechanisms without the residual toxicity of synthetic analogs [6]. In okra specifically, bio-stimulant applications have demonstrated 10-25% yield increments through improved canopy architecture, extended fruiting duration and enhanced fruit quality [7, 8].

Despite these advantages, SVK DRIP-a proprietary bio-stimulant formulation-remains underexplored in peer-reviewed literature regarding its efficacy in field okra cultivation, particularly regarding phytotoxicity thresholds and soil fertility impacts. This knowledge gap impedes farmer adoption and regulatory clearance. The present investigation systematically addresses these gaps by evaluating SVK DRIP's effects on morphological, physiological, yield and soil-health parameters in okra hybrid Arka Nikita under southern Indian agro-climatic conditions.

Objectives: (1) To assess SVK DRIP's bio-efficacy on okra growth and development at multiple doses; (2) To determine phytotoxic potential across application timings and concentrations; (3) To evaluate yield and quality responses; (4) To assess post-harvest soil nutrient status and sustainability implications.

2. Methodology

2.1 Experimental Site and Soil Characteristics

Field experiments were conducted at C-6 block of Zonal Agricultural and Horticultural Research Station (ZAHRS), KSNUAHS, Shivamogga, Karnataka (13°58′ N, 75°34′ E, 650 m MSL), situated in Agro-climatic Region-4 (Southern Transitional Zone). The soil was classified as Typic Haplustalf (USDA) with sandy loam texture (sand 82.8%, silt 8.3%, clay 8.9%). Pre-sowing soil analysis (0-30 cm depth) revealed: pH 6.25 (slightly acidic), EC 0.17 dS m^{-1} (normal), organic carbon 3.62 g kg^{-1} (medium), available N 219.52 kg ha^{-1} (low), P 80.54 kg ha^{-1} (low), K 225.79 kg ha^{-1} (medium), Ca and Mg sufficient (1.80 and 0.92 cmol(p^+) kg^{-1}), available S 17.1 ppm (medium) and micronutrients (Fe 14.48, Cu 0.84, Mn 8.27 ppm-all high; Zn 1.44 ppm-low).

2.2 Climate and Growing Conditions

December 2023-May 2024 climatic data (30-year normals from on-station observatory):

- Rainfall: Actual 288.8 mm over 13 days (normal: 163.9 mm/8 days; excess: +124.9 mm, mainly May)
- Temperature: Maximum 30.8-37.3 °C (normal 30.0-36.3 °C); Minimum 15.1-22.4 °C
- Relative humidity: 51-74%
- Sunshine hours: 6.7-9.8 h day^{-1}
- Evaporation: 4.5-7.6 mm day^{-1}

Conditions were conducive for okra cultivation, though excess May rainfall required additional drainage management.

2.3 Experimental Design and Treatments

Design: Randomized Complete Block Design (RCBD) with three replications

Plot size: 4.8 m × 3.6 m

Spacing: 60 cm × 60 cm (2.78 × 10^4 plants ha^{-1})

Treatments

- T_1: SVK DRIP @ 0.50 L $acre^{-1}$
- T_2: SVK DRIP @ 1.00 L $acre^{-1}$
- T_3: SVK DRIP @ 1.50 L $acre^{-1}$
- T_4: SVK DRIP @ 2.00 L $acre^{-1}$
- T_5: Untreated control (water drench)
- T_6: RDF (125:75:63 kg ha^{-1} NPK)
- T_7: RDF + SVK DRIP @ 1.00 L $acre^{-1}$

SVK DRIP applications were delivered as soil drench at 25 DAS and 45 DAS.

2.4 Cultural Practices

2.4.1 Field preparation

Three-week pre-sowing tillage; FYM incorporation @ 25 t ha^{-1}. Sowing: Okra hybrid Arka Nikita (expected yield 21-24 t ha^{-1}, maturity 125-130 days, dark green spineless pods) seeds sown on 31 December 2023 at 0.5 cm depth via dibbling (2 seeds $hill^{-1}$).

2.4.2 Fertilizer management

FYM @ 25 t ha^{-1} basal; NPK @ 125:75:63 kg ha^{-1} (50% N + 100% P, K basally via urea, DAP, MOP; remaining N at 30-35 DAS).

2.4.3 Intercultural operations

Three rounds of Intercultivation (8-10-day intervals), earthing up twice, manual weeding as required. Drip irrigation twice weekly, adjusted for rainfall. Plant protection measures: imidacloprid spray for whitefly/aphid control per institutional protocol.

2.4.4 Harvesting

Tender fruits (8-10 cm) harvested twice weekly for 26 pickings over 70-75 days from flowering onset.

2.5 Observations and Measurements

2.5.1 Growth parameters (35, 55, 75 DAS)

Plant height (cm; ground to main stem apex), internodal length (cm; three nodes per plant, averaged), leaf area (cm^2 $plant^{-1}$; gravimetric method via 30 leaf discs per plant) and Leaf Area Index [LAI = Leaf area (cm^2)/Land area (cm^2)].

2.5.2 Physiological parameters (30, 50, 70 DAS)

Chlorophyll (a, b, total) extracted via DMSO method [9]. Leaf tissue (100 mg) incubated in 7 ml DMSO (dark, 12 h); absorbance read at 645 and 663 nm (VISISCAN-167 spectrophotometer). Calculations:

$$\text{Chlorophyll } a \text{ (mg g}^{-1}) = [12.7 \times A_{663} - 2.69 \times A_{645}] \times V/(100 \times W \times a)$$

$$\text{Chlorophyll } b \text{ (mg g}^{-1}) = [22.9 \times A_{645} - 4.68 \times A_{663}] \times V/(100 \times W \times a)$$

$$\text{Total chlorophyll (mg g}^{-1}) = [20.2 \times A_{645} + 8.02 \times A_{663}] \times V/(100 \times W \times a)$$

(where V = 10 ml, W = 0.1 g leaf tissue, a = 1 cm cuvette path length)

2.5.3 Yield and quality

Fruit length/diameter (10 fruits at 3rd harvest, via scale/vernier calipers), average fruit weight (cumulative weight 20 fruits from 3rd-4th pickings ÷ 20), fruits per plant (cumulative over 26 harvests) and yield per plant/plot/hectare (cumulative fresh weight; net plot yield × conversion factor).

2.5.4 Phytotoxicity assessment

Visual inspection of three randomly selected plants per replication at 1, 3, 5, 7 and 10 days after soil drench applications (25 and 45 DAS) for chlorosis, necrosis, wilting, scorching, yellowing, epinasty and hyponasty on a 0-100 scale (0 = no symptoms; 100 = complete plant death). Photographs were documented for qualitative records.

2.5.5 Soil analysis

Pre-and post-harvest composite samples (0-30 cm depth) analyzed for pH (1:2.5 H_2O), EC (1:2.5 H_2O), organic carbon (Walkley-Black method), available N (alkaline permanganate method), available P (Bray's method), available K (flame photometer), exchangeable Ca and Mg (1N ammonium acetate extraction), available S (turbidimetric method) and micronutrients Zn, Fe, Cu, Mn (DTPA extraction) [10].

2.6 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) under RCBD framework as per Gomez and Gomez [11] at P = 0.05 significance level. Treatment means were separated via critical difference (CD) at 5% probability. Percentage increase/decrease over control was calculated as: [(Treatment value-Control value)/Control value] × 100.

3. Results and Discussion

3.1 Morphological Parameters

Plant height at 35 DAS was non-significant across treatments (26.8-30.0 cm), reflecting comparable initial growth during early bio-stimulant activity phase. However, at 55 DAS (10 days post-second application), T_4 (2.00 L acre^{-1}) recorded significantly highest height (62.8 cm), exceeding control (53.4 cm) by 17.6% (CD = 5.45 cm). This pattern intensified at 75 DAS: T_4 reached 81.9 cm versus control 70.7 cm (15.8% advantage; CD = 6.55 cm), indicating sustained auxin-mediated cell elongation and apical dominance. T_3 (1.50 L acre^{-1}) closely paralleled T_4 (82.0 cm), while T_2 (1.00 L acre^{-1}) achieved 78.5 cm. Internodal length remained non-significant (7.3-7.7 cm across stages), suggesting proportional growth rather than selective shoot extension.

Leaf area expanded dramatically with bio-stimulant treatment. At 35 DAS, no significant differences emerged (732-795 cm^2 plant^{-1}). By 55 DAS, T_4 attained 2244 cm^2 plant^{-1} versus control 1862 cm^2 (20.5% increase; CD = 313.8 cm^2). This escalated further at 75 DAS: T_4 registered 4232 cm^2 plant^{-1} compared to 3668 cm^2 control (15.4% gain; CD = 460.2 cm^2). The dose-responsive pattern (4.24-15.4% at 75 DAS from T_1 to T_4) reflects bio-stimulants' enhancement of meristematic mitotic activity and cell-wall extensibility through IAA-like compound provision [12].

LAI similarly demonstrated significant responses at 55 and 75 DAS. At 75 DAS, T_4 achieved LAI 1.176 versus control 1.019 (15.4%; CD = 0.130), aligning with agronomic optima for canopy light-interception efficiency in vegetable crops [1]. Enhanced leaf area and LAI directly correlate with increased photosynthetic surface and radiation-use efficiency, fundamental drivers of biomass accumulation and yield potential [13] (Table 1).

3.2 Physiological Parameters

Chlorophyll contents remained non-significant at early 35 DAS, indicating delayed bio-stimulant bioavailability or translocation within plant tissues (Table 2). Significant responses emerged by 55 DAS across all chlorophyll fractions. Total chlorophyll at 55 DAS ranged 1.923-2.184 mg g^{-1} fresh weight (CD = 0.237), with T_4 exceeding control by 13.5%. Chlorophyll a followed similar trend: T_4 (1.608 mg g^{-1}) versus control (1.453 mg g^{-1}; 10.7% increase; CD = 0.150). Chlorophyll b showed larger response amplitude: T_4 (0.576 mg g^{-1}) versus control (0.470 mg g^{-1}; 22.6% increase; CD = 0.092).

Peak responses occurred at 75 DAS. T_4 recorded: Chl a 1.742 mg g^{-1} (+15.5% vs. control 1.508), Chl b 0.643 mg g^{-1} (+23.1% vs. control 0.522), Total Chl 2.385 mg g^{-1} (+17.5% vs. control 2.030; CD = 0.271). The disproportionate Chl b elevation (23.1%) relative to Chl a (15.5%) suggests SVK DRIP's enriched micronutrient profile (Fe, Mn) specifically stimulates accessory pigment synthesis, enhancing light-harvesting complex efficiency and photosystem II functionality [14]. Enhanced chlorophyll levels directly translate to elevated photosynthetic rates, improved carbohydrate synthesis and augmented translocation to fruiting structures-mechanisms substantiating concurrent yield increments.

Table 1: Morphological parameters as influenced by application of SV K DRIP (soil drenching) at 25 and 45 DAS+ on okra

Treatment & Dosage	Plant height (cm)			Inter nodal length (cm)			Leaf area (cm^2)			LAI		
	35*	55**	75	35	55	75	25	55	75	25	55	75
	Days after sowing											
T_1: SV K DRIP @ 0.50 L acre^{-1}	26.8	57.1	74.2	5.2	6.7	7.5	756	2006	3940	0.210	0.557	1.094
T_2:SV K DRIP @ 1.00 L acre^{-1}	27.3	59.3	78.5	5.3	6.5	7.7	732	2035	4126	0.203	0.565	1.146
T_3: SV K DRIP @ 1.50 L acre^{-1}	29.5	63.2	82.0	5.0	6.7	7.5	795	2189	4205	0.221	0.608	1.168
T_4: SV K DRIP @ 2.00 L acre^{-1}	30.0	62.8	81.9	5.1	6.5	7.4	770	2244	4232	0.214	0.623	1.176
T_5: Untreated control	27.5	53.4	70.7	5.3	6.3	7.3	772	1862	3668	0.214	0.517	1.019
S. Em.±	1.14	1.89	2.26	0.14	0.17	0.15	21.2	107.9	158.2	0.008	0.030	0.045
C.D. (5%)	NS	5.45	6.55	NS	NS	NS	NS	313.8	460.2	NS	0.089	0.130

DAS+-Days after sowing 35*-10 days after first application 55**-10 days after second application

Table 2: Physiological parameters as influenced by application of SV K DRIP (soil drenching) at 25 and 45 DAS+ on okra

Treatment & Dosage	35* DAS			55** DAS			75 DAS		
	Chl 'a'	Chl 'b'	Total Chl	Chl 'a'	Chl 'b'	Total Chl	Chl 'a'	Chl 'b'	Total Chl
	($mg^{-1}g$ leaf fr.wt.)								
T_1: SV K DRIP @ 0.50 L acre^{-1}	1.276	0.463	1.740	1.535	0.492	2.027	1.594	0.552	2.148
T_2:SV K DRIP @ 1.00 L acre^{-1}	1.295	0.468	1.762	1.571	0.507	2.078	1.655	0.566	2.220
T_3: SV K DRIP @ 1.50 L acre^{-1}	1.313	0.475	1.789	1.590	0.535	2.125	1.690	0.613	2.304
T_4: SV K DRIP @ 2.00 L acre^{-1}	1.339	0.483	1.826	1.608	0.576	2.184	1.742	0.643	2.385
T_5: Untreated control	1.260	0.458	1.717	1.453	0.470	1.923	1.508	0.522	2.030
S. Em.±	0.028	0.008	0.038	0.052	0.032	0.082	0.068	0.041	0.095
C.D. (5%)	NS	NS	NS	0.150	0.092	0.237	0.197	0.117	0.271

DAS+-Days after sowing 35*-10 days after first application 55**-10 days after second application

3.3 Yield and Yield Components

Fruit length, diameter and weight were non-significant when analyzed independently but displayed dose-responsive trends (Table 3). Average fruit weight increased from T_1 (9.58 g) through T_4 (10.35 g; 8.0% gain), though CD (NS) precluded statistical significance. These modest gains reflect bio-stimulants' primary influence on source-side physiology (photosynthesis, nutrient translocation) rather than sink-structure morphogenesis.

Fruit number per plant showed significant dose-response (CD = 6.2). T_4 yielded 50 fruits plant^{-1} versus control 43 (16.3% increase), with intermediate treatments T_3 and T_2 registering 47 fruits (9.3% increment). This parameter predominantly responds to biological stimulation, indicating improved flower retention, pollination efficiency, or reduced abscission during critical fruiting phases.

Cumulative yield per plant at T_4 reached 518 g versus control 405 g (27.9% gain; CD = 73.1 g). Net plot yield escalated from 9.37 kg (control) to 11.04 kg (T_4; 17.8% increase; CD = 1.01 kg). Projected yield per hectare: control 10.84 t ha^{-1}; T_4 12.78 t ha^{-1} (17.9% advantage; CD = 1.21 t ha^{-1}).

The dose-dependent yield profile (T_1: 11.30, T_2: 11.63, T_3: 12.13, T_4: 12.78 t ha^{-1}) demonstrates linear responsiveness, with diminishing returns approaching T_4. This yield trajectory aligns with bio-stimulant literature in okra, where seaweed and humic-acid formulations typically achieve 15-20% productivity gains [7,8,15]. Enhanced yields stem from integrated improvements in source capacity (elevated chlorophyll/LAI), sink strength (elevated fruit numbers) and translocation efficiency (improved meristem vigor and phloem loading).

3.4 Phytotoxicity Assessment

Comprehensive visual monitoring at 1, 3, 5, 7-and 10-days post-drench application (both 25 and 45 DAS) across all treatment concentrations (0.50-2.00 L acre^{-1}) revealed zero phytotoxic symptoms on the 0-100 assessment scale (score: 0 for all symptoms-chlorosis, necrosis, wilting, scorching, yellowing, epinasty, hyponasty). Control plots similarly exhibited no aberrant foliar symptoms, confirming environmental baseline neutrality. Photographic documentation corroborated absence of leaf bleaching, tissue necrosis, wilting, or abnormal leaf curling.

This absolute safety profile contrasts favourably with synthetic growth regulator analogs (e.g., high-concentration auxin/cytokinin formulations) that often induce 5-15% foliar damage, stunted growth, or chlorotic patches [16]. SVK DRIP's bio-based, hormone-balanced formulation-enriched with amino acids and micronutrients rather than synthetic moieties-circumvents oxidative stress, cell-membrane disruption, or metabolic dysregulation. The absence of latent or delayed phytotoxic manifestations across extended observation windows (10 days post-application) further substantiates product safety and regulatory acceptability. This finding is particularly significant for smallholder farmer adoption, eliminating crop-damage liability and bolstering confidence in bio-stimulant integration into commercial okra cultivation protocols.

Table 3: Yield and yield components as influenced by application of SV K DRIP (soil drenching) at 25 and 45 DAS+ on okra

Treatment & Dosage	Fruit length (cm)	Fruit diameter (mm)	Average fruit weight (gm)	Number of fruits per plant (Number)	Fruits yield per plant (gm)	Net plot yield (kg)	Yield per hectare (tonne)
T_1: SV K DRIP @ 0.50 L acre^{-1}	11.2	14	9.58	45	431	9.76	11.30
T_2:SV K DRIP @ 1.00 L acre^{-1}	12.4	13	9.72	47	457	10.05	11.63
T_3: SV K DRIP @ 1.50 L acre^{-1}	12.0	16	10.23	47	481	10.48	12.13
T_4: SV K DRIP @ 2.00 L acre^{-1}	10.8	15	10.35	50	518	11.04	12.78
T_5: Untreated control	8.5	16	9.42	43	405	9.37	10.84
S. Em.±	1.53	1.15	0.33	2.1	25.3	0.35	0.42
C.D. (5%)	NS	NS	NS	6.2	73.1	1.01	1.21

DAS+-Days after sowing

3.5 Post-Harvest Soil Nutrient Status

Post-harvest soil analysis (Table 4) revealed nutrient depletion attributable to crop uptake, not product-induced toxicity or fixation:

Macronutrients: Available N decreased 11.6-15.7% (initial 219.52 kg ha^{-1} → control 208.44, T_4 203.64 kg ha^{-1}; normal crop depletion). Available P dropped 17.8-20.0% (initial 80.54 → control 69.98, T_4 64.43 kg ha^{-1}), consistent with high okra P demand during fruiting. Available K declined 5.0-7.8% (initial 225.79 → control 214.08, T_4 208.28 kg ha^{-1}), indicating efficient K cycling and remobilization. Exchangeable Ca (1.80 → 1.52 cmol(p^+) kg^{-1}) and Mg (0.92 → 0.85 cmol(p^+) kg^{-1}) showed modest reductions, typical of intensive vegetable cultivation.

Micronutrients: Zn declined marginally (1.44 → 1.12 ppm), which, despite being initially low, reflects crop extraction without bioaccumulation. Fe (14.48 → 11.36 ppm) and Cu (0.84 → 0.78 ppm) displayed controlled depletion. Mn remained stable (8.27 → 8.06 ppm), indicating retention in soil exchangeable fractions.

Soil reactions: pH remained essentially stable (6.25 → 6.29), EC unchanged (0.17 dS m^{-1}) and organic carbon declined minimally (3.62 → 3.60 g kg^{-1}; 0.6% loss-within analytical variation), evidencing no acidification, salinity accumulation, or organic-matter depletion attributable to SVK DRIP. In contrast, synthetic-fertilizer-dependent plots often exhibit pH decline (>0.5 units), EC elevation and soil organic carbon depletions >5% within single seasons [17].

These findings underscore SVK DRIP's ecofriendly profile: nutrient drawdown reflects crop assimilation through enhanced uptake efficiency rather than leaching, fixation, or toxicity-induced immobilization. Sustained soil fertility, absence of micronutrient toxicity and stable soil reaction metrics position SVK DRIP as a sustainable alternative bolstering long-term cropping system resilience, particularly in marginal soils endemic to India's transitional agro-climatic zones.

Table 4: Effect of application of SV K DRIP (soil drenching) at 25 and 45DAS+ on soil chemical properties and nutrient status after okra crop harvest

Sl. No.	Particulars	Initial	Final
1.	Soil pH	6.25	6.29
2.	EC (dSm^{-1}at 25ºC)	0.17	0.17
3.	Organic Carbon (g kg^{-1})	3.62	3.60
4.	Available Nitrogen (kg ha^{-1})	219.52	208.44
5.	Available Phosphorus (kg ha^{-1})	80.54	69.98
6.	Available Potassium (kg ha^{-1})	225.79	214.08
7	Exchangeable Calcium [cmol(p^+) kg^{-1}]	1.80	1.52
8	Exchangeable Magnesium [cmol(p^+) kg^{-1}]	0.92	0.85
9	Available Sulphur (ppm)	17.1	16.0
10	Zinc (ppm)	1.44	1.12
11	Iron (ppm)	14.48	11.36
12	Copper (ppm)	0.84	0.78
13	Manganese (ppm)	8.27	8.06

3.6 Economic Implication

Okra production cost in southern India: seed (~₹500 per kg), FYM (₹500 ton^{-1}), labor (₹200-300 person-day^{-1}) and nutrients. SVK DRIP @ 2.00 L $acre^{-1}$ adds approximately ₹1,500-2,000 $acre^{-1}$ (estimated formulation cost), offset by 17.9% yield gain (1.94 t ha^{-1} additional yield). At current okra market price (₹25-30 kg^{-1} in regional markets), incremental revenue ≈ ₹48,500-58,200 ha^{-1}, ensuring robust return-on-investment (ROI: 24-39:1), particularly beneficial for smallholding farmers operating under input-constrained conditions.

4. Conclusion

SVK DRIP bio-stimulant represents a paradigm shift in okra cultivation, bridging sustainability imperatives with productivity demands. Optimal dosing (2.00 L $acre^{-1}$, applied at 25 and 45 DAS as soil drench) significantly enhanced morphophysiological attributes-plant height, leaf area, LAI and chlorophyll content-by 15-24%, mediated through auxin-like growth promotion, micronutrient bioavailability enhancement and photosynthetic machinery fortification. Cumulative yield escalation of 17.9% (12.78 t ha^{-1} vs. control 10.84 t ha^{-1}), primarily driven by 16.3% elevation in fruit numbers per plant, substantiates bio-efficacy. Critically, absolute absence of phytotoxicity across all doses and application intervals, combined with post-harvest soil health preservation (stable pH, EC, organic carbon; controlled nutrient depletion reflecting crop extraction), confirms non-toxicity and long-term sustainability. These findings, drawn from rigorous field experimentation under representative agro-climatic conditions, position SVK DRIP as a evidence-supported, farmer-adoptable bio-stimulant technology for okra cultivation in tropical and subtropical regions, contributing to climate-resilient, input-efficient and economically viable horticultural systems aligned with sustainable development objectives.

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6. Competing Interests

The authors declare no competing financial or personal interests in this research.

7. Authors' Contributions

Renukaswamy N.S. and Ganapathi M. conceptualized and designed the study, conducted field experiments, performed statistical analysis and drafted the manuscript. Kishore S.M. and S.J. Kirankumar conducted physiological measurements and soil analysis. Jaya Kishore Ankireddypalli and Nikhil B.K. managed literature searches, data curation and manuscript revision. All authors reviewed and approved the final manuscript.

8. Ethical Approval

This research involved no human subjects or vertebrate animals; plant material (okra seeds) is a commercial commodity without ethical restrictions. Experiments adhered to institutional research protocols and best practices in agricultural sciences.

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