



RESEARCH ARTICLE

Silicon-mediated sustainable intensification of rice production: Impacts on yield, economic returns and pest resistance

Kavipriya M^{1*}, S Ramesh¹, P Sudhakar¹, S Manimaran¹, D Venkatakrishnan² & M Dhayanethi¹

¹Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India

²Department of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India

*Correspondence email - kavipriyamegarajan@gmail.com

Received: 04 January 2026; Accepted: 27 July 2026; Available online: Version 1.0: 01 September 2026

Cite this article: Kavipriya M, Ramesh S, Sudhakar P, Manimaran S, Venkatakrishnan D, Dhayanethi M. Silicon-mediated sustainable intensification of rice production: Impacts on yield, economic returns and pest resistance. Plant Science Today. 2026; 13(sp5): 1-7. <https://doi.org/10.14719/pst.13529>

Abstract

Rice cultivation is increasingly constrained by stagnant yields, diminishing profit margins and escalating pest pressures. These interrelated challenges compromise both crop productivity and economic viability. To address this, the adoption of integrated agronomic strategies is essential. The precise application of micronutrients and biostimulants has been shown to improve physiological efficiency, enhance nutrient-use efficiency and activate plant defence responses, thereby contributing to increased yield performance, economic returns and pest resilience under sustainable production systems. Therefore, a field study was carried out during the 2024 kuruvai season (June–September) at the Experimental Farm of the Department of Agronomy, Faculty of Agriculture, Annamalai University, Tamil Nadu. To assess the treatment effects, the experiment followed a split-plot design with 3 replications. The main plot treatments consisted of four micronutrient regimes: an untreated control (M_1), zinc sulphate ($ZnSO_4$) applied at 25 kg ha^{-1} (M_2), diatomaceous earth applied at 50 kg ha^{-1} as a silicon source (M_3) and a combined application of $ZnSO_4$ at 25 kg ha^{-1} and diatomaceous earth at 50 kg ha^{-1} (M_4). The subplot treatments consisted of four biostimulant regimes: an untreated control (S_1), humic acid applied at 0.3 % (S_2), seaweed extract applied at 0.3 % (S_3) and vermiwash applied at 5 % (S_4). Among all treatment combinations, the application of $ZnSO_4$ at 25 kg ha^{-1} along with diatomaceous earth at 50 kg ha^{-1} , supplemented by foliar sprays of seaweed extract (0.3 %) at 20 and 40 days after transplanting (DAT) (M_4S_3), recorded the highest grain yield (6270 kg ha^{-1}) and straw yield (8783 kg ha^{-1}), resulting in the maximum net income ($₹89209.5\text{ ha}^{-1}$) and benefit-cost ratio (2.44). The treatment also significantly reduced leaf folder incidence to 0.81 %, indicating enhanced productivity, profitability and pest tolerance.

Keywords: biostimulants; integrated nutrient management; micronutrients; pest populations; productivity

Introduction

Rice (*Oryza sativa* L.), often referred to as the grain of life, serves as the primary food source for approximately 65 % of India's population and fulfils a substantial portion of dietary requirements by providing starch, protein and essential micronutrients. To maintain national self-sufficiency, annual milled rice production must increase by about 2.5 million tonnes. In Tamil Nadu, rice is cultivated over 2.16 million hectares, with a production of 7.09 million tonnes and an average productivity of 3288 kg ha^{-1} during 2024–25, highlighting its crucial role in the state's agricultural economy and food security. In terms of nutritional security and caloric intake, rice is of paramount importance, accounting for 42 % of the country's total food grain production and 45 % of overall cereal output. In developing nations, rice accounts for 50–80 % of daily energy consumption, a share that surpasses that of maize or wheat. Long periods of intensive land use, combined with improper nutrient management practices, lead to declines in crop yields and the depletion of available soil nutrients (1). Proper soil nutrient management forms the backbone of successful crop production, playing a key role in both raising and maintaining high yields over time. Among the various micronutrients, zinc stands out as particularly critical for plant growth, especially in rice cultivated

under waterlogged conditions. Plants absorb zinc in its Zn^{2+} ionic form and although required only in small quantities, this element is indispensable for several growth and metabolic processes. Its importance stems largely from its role as an integral component of numerous enzymes and as an essential activator of many metabolic reactions within the plant system. It is also required for protein synthesis and gene expression in plants. Silicon is not considered an essential element but is recognised as beneficial for crop growth, especially in crops of the family Poaceae (2). In cereal crops, silicon plays an important role in reducing the risk of lodging, a significant concern for agricultural productivity. It also contributes to improved disease resistance, enhanced light absorption and more efficient water use. Additionally, silicon supports photosynthesis and helps correct nutrient imbalances within the plant. It also increases the mechanical strength of the culm, thereby reducing crop lodging and improving leaf angle, making leaves more erect and reducing self-shading (3). Biostimulants are naturally derived products that enhance plant growth, nutrient acquisition, crop productivity, quality and resilience to biotic and abiotic stresses. They include diverse substances such as botanical extracts, protein hydrolysates, amino acids, vitamins, microbial inoculants, antioxidants and anti-transpirants. Humic acid, a major component of soil organic matter, improves root growth, nutrient

availability and soil microbial activity, thereby promoting overall plant development. Seaweed extract contains a range of bioactive compounds, including phytohormones, amino acids, vitamins and micronutrients, which stimulate physiological and biochemical processes and enhance stress tolerance. Vermiwash, a liquid by-product of vermicomposting, is enriched with nutrients, beneficial microorganisms, enzymes and plant growth regulators that support plant metabolism and crop performance. Through improved nutrient-use efficiency and reduced dependence on synthetic agrochemicals, biostimulants contribute to sustainable crop production and the long-term stability of agroecosystems. Although the individual roles of zinc, silicon and biostimulants in improving rice performance have been extensively studied, research on their combined application is still limited. In particular, information regarding their synergistic effects on yield, economic returns and pest management in rice under the agro-climatic conditions of Tamil Nadu remains scarce. Therefore, the present study was undertaken to evaluate the effect of integrated application of zinc and silicon in combination with biostimulants on the growth, yield, economics and pest incidence of rice under the conditions of Tamil Nadu.

Materials and Methods

The field study was conducted from June to September 2024 at the Experimental Farm of the Department of Agronomy, Annamalai University, located in Annamalai Nagar, Tamil Nadu. Geographically, the site lies at 11° 24' N latitude and 79° 44' E longitude, at an elevation of 5.79 m above mean sea level. During the experimental period, the maximum temperatures recorded ranged from 34.2 °C to 37.5 °C, with an average of 36.16 °C, while the minimum temperatures ranged from 20.1 °C to 22.8 °C, averaging 21.65 °C. The rice crop received a total rainfall of 182.0 mm distributed over 14 rainy days. The soil of the experimental field is classified as Udic Chromustert (4) with a pH of 7.45, electrical conductivity of 0.36 dS m⁻¹, organic carbon content of 0.46 %, available nitrogen (N) of 225 kg ha⁻¹, available phosphorus (P) of 22 kg ha⁻¹ and available potassium (K) of 282 kg ha⁻¹ before transplanting. The promising rice variety ADT 43 was chosen for this study. The experimental layout followed a split-plot design, comprising 4 treatments in the main plot and 4 treatments in the sub-plot. The main plot treatments included a control, soil application of zinc sulphate (ZnSO₄) at 25 kg ha⁻¹, soil application of diatomaceous earth (DE) at 50 kg ha⁻¹ and a combined soil application of ZnSO₄ at 25 kg ha⁻¹ along with DE at 50 kg ha⁻¹. In the subplots, the treatments consisted of a control, a foliar application of humic acid at 0.3 %, a foliar spray of seaweed extract at 0.3 % and a foliar spray of vermiwash at 5 %, all applied at 20 and 40 days after transplanting (DAT). The treatments were replicated thrice. The recommended quantity of paddy seeds (ADT 43 at 60 kg ha⁻¹) was treated with carbendazim at 2 g kg⁻¹ of seeds. Further, the seeds were treated with *Bacillus subtilis* at 600 g ha⁻¹. After treatment, the seeds were soaked in water for 24 hr and then kept inside gunny bags for 48 hr to allow sprouting. These sprouted seeds were later sown in the nursery beds. A uniform fertiliser schedule was followed for all plots, applying the recommended dose of 120 : 40 : 40 kg of N, P as P₂O₅ and K as K₂O per hectare. The sources used were urea (46 % N), single superphosphate (16 % P₂O₅) and muriate of potash (60 % K₂O). Nitrogen and potash were each given in four equal splits at basal, tillering, panicle initiation and heading stages, while the full dose of P was applied as a basal dressing before transplanting. Eighteen-day-old seedlings were transplanted at two per hill,

maintaining a spacing of 15 cm between rows and 10 cm between plants. To record growth and yield attributes, five sample plants were randomly selected from each plot and permanently marked. At harvest, the border rows were excluded to avoid edge effects and only the net plot area was harvested. The harvested grains were hand-threshed, winnowed and sun-dried until the moisture content was 14 %. Grain yield was recorded plot-wise and later converted to kilograms per hectare. Economic analysis was carried out by accounting for all input costs, labour expenses and prevailing market prices of the produce. Gross and net returns per hectare were calculated and the benefit–cost ratio (BCR) was derived by dividing gross returns by the total cultivation cost for each treatment.

Assessment of rice leaf folder per cent incidence

To assess the incidence of rice leaf folder (*Cnaphalocrocis medinalis*), 10 hills were randomly selected from each plot. From these, both the total number of leaves and those showing visible damage were counted. The extent of leaf damage was then expressed as a percentage using the following formula.

$$\text{Per cent incidence} = \frac{\text{Number of damaged leaves}}{\text{Total number of leaves}} \times 100$$

Statistical analysis

The data on various characters studied during the field investigation were statistically analysed as suggested by previous researchers (5) and wherever treatment differences were found significant (*F* test), critical differences were calculated at the 5 % probability level and the values are furnished. Treatment differences that were not significant were denoted as “NS”.

Results and Discussion

Plant height

Morphometric response of plant height to main plot effects

Plant height was significantly greatest under M₄ (ZnSO₄ at 25 kg ha⁻¹ + DE at 50 kg ha⁻¹) at 97.67 cm, while the lowest was recorded under M₁ (no ZnSO₄, no DE) at 80.89 cm (Table 1). This response reflects the complementary physiological roles of zinc and silicon on shoot development. Zinc, as a cofactor for tryptophan synthase, regulates IAA biosynthesis and sustains auxin-mediated cell elongation in internodal meristems, while silicon deposited as amorphous silica in epidermal and sclerenchyma tissues reinforces culm rigidity and upright leaf architecture, allowing that elongation to express fully as standing plant height. These findings are consistent with earlier reports on improved plant height in rice under zinc and silicon application (6, 7).

Morphometric response of plant height to subplot factors

Foliar application of seaweed extract at 0.3 % at 20 and 40 DAT recorded the highest plant height at 93.00 cm, while the unsprayed control recorded the lowest at 84.03 cm. Seaweed extract supplies endogenous cytokinins, auxins and gibberellins that stimulate meristematic cell division and internodal elongation, alongside iron and manganese that sustain photosynthetic capacity to support vegetative growth. Spray timing at 20 and 40 DAT coincided with active tillering and stem elongation, ensuring growth regulators were available during peak meristematic responsiveness. These findings are consistent with earlier reports on seaweed extract-mediated improvement in rice plant height (8).

Table 1. Effect of micronutrients and biostimulants on plant height (cm) at 30, 60 DAT and at harvest stage in transplanted rice

Treatments	30 DAT					60 DAT					Harvest				
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
S ₁	34.56	43.90	38.07	49.75	41.57	58.97	69.22	63.71	77.92	67.46	77.74	85.59	80.89	91.88	84.03
S ₂	40.92	52.83	46.82	57.06	49.41	65.15	81.72	73.71	87.29	76.97	82.46	94.99	88.76	99.63	91.46
S ₃	42.29	54.09	48.01	58.95	50.84	67.50	83.14	75.17	89.86	78.92	84.03	96.56	90.34	101.08	93.00
S ₄	36.54	51.18	45.19	55.91	47.21	60.83	79.01	71.89	85.90	74.41	79.31	93.43	87.17	98.10	89.50
Mean	38.58	50.50	44.52	55.42		63.11	78.27	71.12	85.24		80.89	92.64	86.79	97.67	
	M	S	M at S	S at M		M	S	M at S	S at M		M	S	M at S	S at M	
S.Ed	0.27	0.28	0.55	0.56		0.33	0.37	0.72	0.74		0.33	0.42	0.79	0.83	
CD (<i>p</i> = 0.05)	0.66	0.57	1.14	1.15		0.81	0.76	1.49	1.52		0.82	0.86	1.64	1.71	

DAT: days after transplanting.

Treatment details:

Main plots: M₁- Control

M₂ - Soil application of ZnSO₄ at 25 kg ha⁻¹

M₃ - Soil application of diatomaceous earth at 50 kg ha⁻¹

M₄ - Soil application of ZnSO₄ at 25 kg ha⁻¹ + diatomaceous earth at 50 kg ha⁻¹

Sub-plots: S₁ - Control

S₂ - Foliar spray of 0.3 % Humic acid (20 and 40 DAT)

S₃ - Foliar spray of 0.3 % Seaweed extract (20 and 40 DAT)

S₄ - Foliar spray of 5 % Vermiwash (20 and 40 DAT)

Interactive influence of main and subplot treatments on plant height dynamics

The interaction treatment M₄S₃ (ZnSO₄ at 25 kg ha⁻¹ + DE at 50 kg ha⁻¹ + seaweed extract at 0.3 %) recorded the highest plant height at 101.08 cm, while M₁S₁ (no ZnSO₄, no DE, water spray) recorded the lowest at 77.74 cm. This response reflects the convergence of three complementary mechanisms. Zinc sustained auxin biosynthesis via tryptophan synthase activity and supported chlorophyll production, driving cell division and internodal elongation. Silicon deposited in epidermal and sclerenchyma tissues reinforced culm rigidity and promoted erect leaf architecture, improving light interception within the canopy and enhancing photosynthetic efficiency. Seaweed extract contributed bioavailable IAA, gibberellins and cytokinins that further stimulated meristematic activity, alongside micronutrients, vitamins and amino acids that supported overall metabolic function. The additive expression of these inputs through soil applied mineral nutrition, structural silicon and foliar biostimulation collectively explains the height advantage observed under M₄S₃ over all other treatment combinations. These findings are supported by earlier reports on silicon mediated structural improvements in rice (9) and seaweed extract as a plant growth biostimulant (10).

Yield

Rice yield potential is largely determined by yield attributes, which exhibit patterns consistent with the corresponding growth parameters (Fig. 1).

Quantitative variation in grain yield under main plot regimes

The highest grain and straw yields of 6001 and 8506 kg ha⁻¹ were recorded under M₄ (ZnSO₄ at 25 kg ha⁻¹ + DE at 50 kg ha⁻¹), representing increases of 31.8 % and 20.31 % over M₁ (no ZnSO₄, no DE), which recorded the lowest grain and straw yields of 4533 and 7070 kg ha⁻¹ respectively. Zinc adequacy activated tryptophan synthase and carbonic anhydrase, sustaining auxin synthesis, carbon fixation and N assimilation, which collectively strengthened source capacity and improved assimilate partitioning toward the grain. Silicon deposited in leaf epidermal cells reduced self-shading and improved canopy light use efficiency, while its role in maintaining cellular turgor and membrane integrity during anthesis enhanced pollen viability and reduced spikelet sterility, directly

supporting grain filling. The combined improvement in source activity through zinc and sink filling through silicon accounts for the yield superiority of M₄ over all other main plot treatments. These findings agree with earlier reports on zinc mediated yield improvement in rice (11) and silicon fertilisation effects on rice productivity (12).

Quantitative variation in grain yield under subplot regimes

Among subplot treatments, foliar application of seaweed extract at 0.3 % (S₃) recorded the highest grain and straw yields of 5520 and 8012 kg ha⁻¹ respectively, representing increases of 15.99 % and 9.81 % over S₁ (water spray), which recorded the lowest grain and straw yields of 4759 and 7296 kg ha⁻¹ respectively. The bioavailable auxins, cytokinins and gibberellins present in seaweed extract regulated floret initiation and spikelet development, while polysaccharide constituents enhanced root membrane permeability and nutrient uptake during reproductive growth. Micronutrients delivered through seaweed extract further supported enzyme activation and chlorophyll retention during grain filling, sustaining photosynthetic source strength when canopy senescence would otherwise restrict assimilate supply to developing grains. These combined effects improved resource partitioning toward reproductive sinks, accounting for the yield advantage observed under S₃. This is in agreement with earlier reports on seaweed extract improving rice productivity as a biostimulant (13).

Quantitative variation in grain yield under main plot and subplot interaction

The interaction treatment M₄S₃ (ZnSO₄ at 25 kg ha⁻¹ + diatomaceous earth at 50 kg ha⁻¹ + seaweed extract at 0.3 %) recorded the highest grain and straw yields of 6270 and 8783 kg ha⁻¹ respectively, representing increases of 49.89 % and 29.54 % over M₁S₁ (no ZnSO₄, no DE, water spray), which recorded the lowest grain and straw yields of 4183 and 6780 kg ha⁻¹ respectively. Zinc activated carbonic anhydrase and nitrate reductase in root tissue, improving N assimilation and lateral root proliferation, which expanded the absorptive surface area and enhanced translocation of N, P and K to aerial plant parts during grain development. Silicon deposited in epidermal cells promoted erect leaf architecture, reducing mutual shading within the canopy and increasing light use efficiency, while

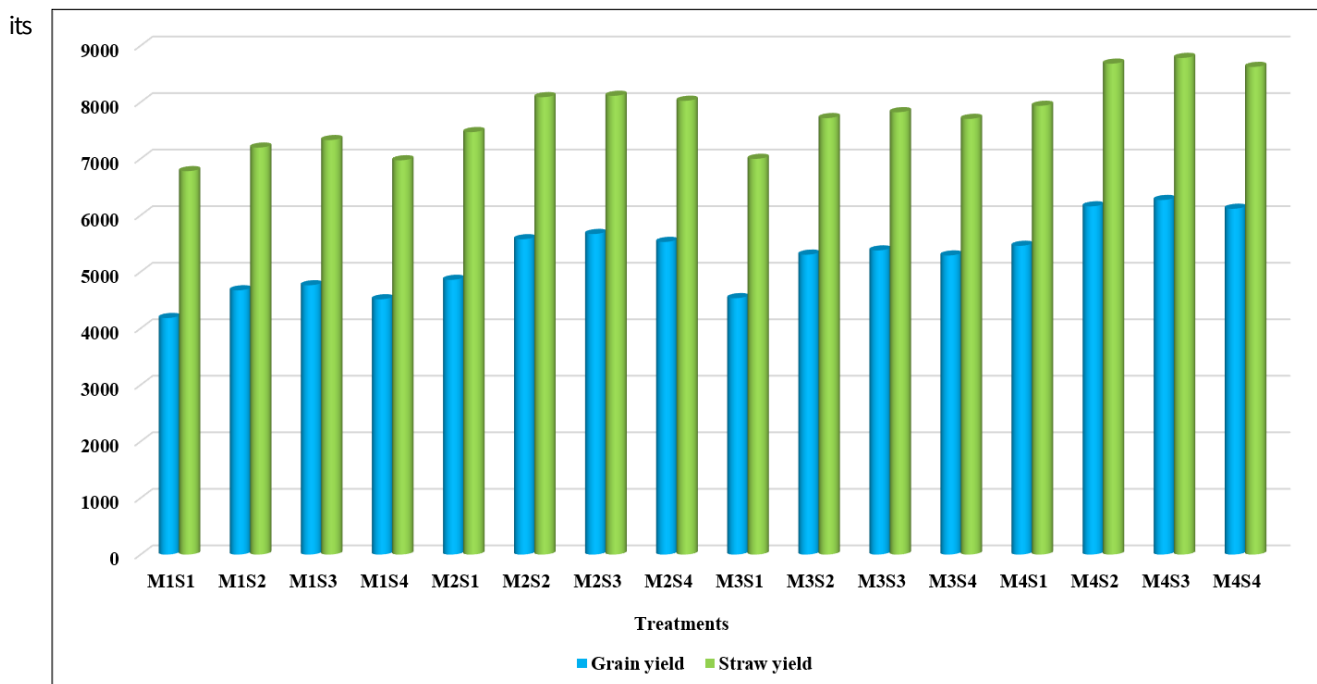


Fig. 1. Effect of micronutrients and biostimulants on grain yield (kg ha⁻¹) and straw yield (kg ha⁻¹) in transplanted rice.

role in reinforcing cell wall integrity reduced pathogen penetration and herbivore damage, directing more assimilates toward reproductive sinks. Seaweed extract supplied magnesium as a direct chlorophyll precursor and cytokinins that delayed flag leaf senescence during grain filling, sustaining photosynthetic source strength through the critical period of starch accumulation in the endosperm. The simultaneous activation of root level nutrient acquisition through zinc, canopy level light capture through silicon and source strength maintenance through seaweed extract collectively accounts for the yield superiority of M₄S₃ over all other interaction treatments. These findings are consistent with earlier reports on zinc mediated yield improvement in rice (6), silicon fertilisation effects on rice growth and nutrient uptake (14) and seaweed extract as a yield enhancing biostimulant (15).

Incidence of pest

Main plot effects on pest dynamics

Among the main plot treatments, M₄ (ZnSO₄ at 25 kg ha⁻¹ + DE at 50 kg ha⁻¹) recorded the lowest leaf folder incidence of 1.33 % and leaf damage of 0.57 %, while M₁ (no ZnSO₄, no DE) recorded the highest at 4.52 % and 3.66 % respectively (Table 2 and 3), with M₃ (DE at 50 kg ha⁻¹ alone) recording intermediate values of 1.41 % and 0.63 %. The suppression of leaf folder incidence under M₄ and M₃ is attributable to silicon accumulation in epidermal and hypodermal tissues, where amorphous silica deposition increases leaf surface hardness and restricts larval feeding and movement. Beyond this physical barrier, silicon supplied at the rates used in the present study triggered salicylic acid and jasmonic acid dependent defence signalling, activating polyphenol oxidase and peroxidase, promoting lignification and inducing systemic acquired resistance, collectively reducing pest susceptibility at the whole plant level. The greater reduction under M₄ compared to M₃ reflects the additional contribution of zinc, which as a cofactor for superoxide dismutase and other defence related enzymes, further strengthened oxidative stress mitigation and reinforced the plant immune response. These findings are consistent with earlier reports on silicon mediated suppression of leaf folder incidence in rice (16).

Subplot effects on pest dynamics

Leaf folder incidence and leaf damage were significantly lowest under S₃ (seaweed extract at 0.3 % at 20 and 40 DAT), recording 1.50 % and 2.66 % incidence and 1.08 % and 1.72 % leaf damage at tillering and flowering respectively, against the highest values of 3.02 %, 4.44 %, 2.48 % and 3.82 % under S₁ (water spray). Seaweed extracts bioactive polysaccharides including laminarin and fucoidan elicited salicylic acid dependent defence pathways, activating peroxidase and chitinase in leaf tissue and reducing larval attachment, while improved canopy architecture under S₃ reduced the humid microclimate favouring leaf folder oviposition and survival. These results are in agreement with earlier reports on seaweed extract mediated suppression of leaf folder incidence in rice (17).

Modulation of pest dynamics by main plot and subplot treatments

Among the interaction treatments, M₄S₃ (ZnSO₄ at 25 kg ha⁻¹ + DE at 50 kg ha⁻¹ + seaweed extract at 0.3 %) recorded the minimum leaf folder incidence of 0.81 % and 2.07 % and leaf damage of 0.25 % and 0.98 % at tillering and flowering stages respectively, while M₁S₁ (no ZnSO₄, no DE, water spray) registered the maximum values of 4.58 % and 6.16 % incidence and 4.29 % and 5.96 % leaf damage at the corresponding stages. The pronounced pest suppression under M₄S₃ reflects the convergence of three non-overlapping defence mechanisms operating simultaneously. Silicon accumulated in epidermal tissues created a physical deterrent to larval feeding while activating polyphenol oxidase and peroxidase through salicylic acid dependent signalling. Zinc supported superoxide dismutase activity and oxidative stress mitigation, limiting tissue damage following larval feeding attempts. Seaweed extracts sustained defence gene expression across tillering and flowering through laminarin and fucoidan mediated priming of induced systemic resistance. The integration of structural, enzymatic and systemic defence pathways under M₄S₃ collectively produced pest suppression beyond what any individual input could achieve, in agreement with earlier reports on silicon based integrated pest management in rice (18).

Table 2. Effect of micronutrients and biostimulants on leaf folder incidence (%) at tillering and flowering stage in rice

Treatments	Tillering					Flowering				
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
S ₁	4.58	4.33	1.65	1.53	3.02	6.16	5.85	2.91	2.82	4.44
S ₂	4.45	4.13	1.56	1.48	2.91	6.07	5.67	2.84	2.75	4.33
S ₃	2.21	2.15	0.84	0.81	1.50	3.26	3.21	2.11	2.07	2.66
S ₄	4.52	4.27	1.59	1.51	2.97	5.98	5.74	2.87	2.79	4.35
Mean	3.94	3.72	1.41	1.33		5.37	5.12	2.68	2.61	
	M	S	M at S	S at M		M	S	M at S	S at M	
S.Ed	0.11	0.14	0.27	0.28		0.13	0.15	0.29	0.31	
CD ($p = 0.05$)	0.26	0.29	0.55	0.58		0.31	0.32	0.61	0.63	

DAT: days after transplanting.

Table 3. Effect of micronutrients and biostimulants on leaf damage (%) due to leaf folder at tillering and flowering stage in rice

Treatments	Tillering					Flowering				
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
S ₁	4.29	4.16	0.77	0.70	2.48	5.96	5.83	1.78	1.71	3.82
S ₂	4.20	4.09	0.72	0.64	2.41	5.87	5.76	1.73	1.65	3.75
S ₃	1.91	1.87	0.28	0.25	1.08	2.45	2.41	1.02	0.98	1.72
S ₄	4.25	4.13	0.74	0.67	2.45	5.91	5.79	1.75	1.68	3.78
Mean	3.66	3.56	0.63	0.57		5.05	4.95	1.57	1.51	
	M	S	M at S	S at M		M	S	M at S	S at M	
S.Ed	0.09	0.12	0.23	0.25		0.10	0.12	0.24	0.25	
CD ($p = 0.05$)	0.23	0.26	0.48	0.51		0.25	0.26	0.49	0.52	

DAT: days after transplanting.

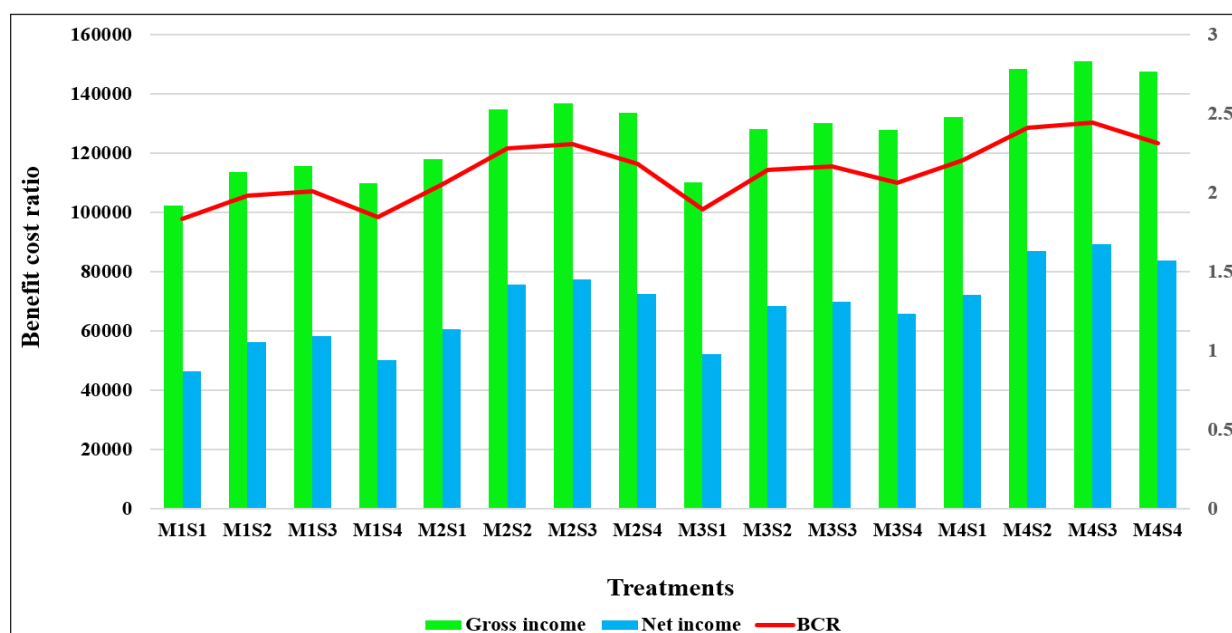
Economics

Maximum gross income of Rs. 151114.5 ha⁻¹, net income of Rs. 89209.5 ha⁻¹ and BCR of 2.44 were obtained under M₄S₃ (ZnSO₄ at 25 kg ha⁻¹ + diatomaceous earth at 50 kg ha⁻¹ + seaweed extract at 0.3 %), whereas minimum gross income of Rs. 102196 ha⁻¹, net income of Rs. 46511 ha⁻¹ and BCR of 1.84 were registered under M₁S₁ (no ZnSO₄, no DE, water spray). The economic superiority of M₄S₃ is a direct outcome of yield gains generated through three complementary input mechanisms: zinc activated carbonic anhydrase and nitrate reductase improving N assimilation and assimilate production; silicon reinforced canopy architecture and induced systemic resistance reducing yield losses from lodging and pest damage; and seaweed extract delayed flag leaf senescence through cytokinin activity, sustaining photosynthetic source strength during grain filling. The BCR of 2.44 under M₄S₃ confirms

that economic returns scaled proportionally with input investment, with higher marketable grain and straw yields directly driving gross and net income per hectare (Fig. 2). The concurrent absence of these inputs under M₁S₁ restricted nutrient acquisition, photosynthetic efficiency and pest tolerance, compressing yield and economic returns to their lowest recorded values. These results agree with earlier reports on economic benefits of seaweed extract in kharif rice (19) and zinc fertilisation economics in rice (20).

Conclusion

The combined application of zinc sulphate (ZnSO₄) at 25 kg ha⁻¹, diatomaceous earth (DE) at 50 kg ha⁻¹ and foliar seaweed extract at 0.3 % at 20 and 40 DAT (M₄S₃) recorded the highest grain yield (6270 kg ha⁻¹), net income (Rs. 89209.5 ha⁻¹), benefit–cost ratio (BCR) (2.44)

**Fig. 2.** Effect of micronutrients and biostimulants on gross income (Rs. ha⁻¹), net income (Rs. ha⁻¹) and benefit cost ratio in transplanted rice.

and the lowest leaf folder incidence under Tamil Nadu agro-climatic conditions. The convergence of zinc mediated nitrogen (N) assimilation, silicon induced structural defence and seaweed extract driven bio stimulation demonstrates that integrated nutrient and pest management can simultaneously optimise productivity, profitability and crop resilience in zinc deficient, pest prone environments of South India. However, these findings are specific to the soil type, season and variety tested and their generalisability across diverse agro-ecosystems warrants further investigation. Future studies should examine residual effects of diatomaceous earth on soil silicon dynamics, seaweed extract interactions under high pest pressure seasons and the economic viability of M_4S_3 across smallholder farm conditions in Tamil Nadu.

Acknowledgements

The authors express their heartfelt gratitude to the advisory committee members and the teaching and non-teaching staff of the Department of Agronomy, Faculty of Agriculture, Annamalai University, Chidambaram, for their invaluable support in providing access to library resources and web-based information sources.

Authors' contributions

KM conducted the experiment, recorded and analysed the data and collected and organised the literature. KM and SR conceptualised and designed the review. PS, SM, MD and DV provided technical input and assisted with manuscript drafting. SR supervised the overall preparation and finalised the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

The authors acknowledge the use of ChatGPT for grammatical corrections and language editing during the preparation of this manuscript. Following its use, the authors thoroughly reviewed and revised the content as necessary and take full responsibility for the accuracy and integrity of the publication.

References

- Meena VD, Dotaniya ML, Coumar V, Rajendiran S, Kundu S, Rao AS. A case for silicon fertilization to improve crop yields in tropical soils. *Proc Natl Acad Sci India Sect B Biol Sci.* 2014;84(3):505–18. <https://doi.org/10.1007/s40011-013-0270-y>
- Guntzer F, Keller C, Meunier JD. Benefits of plant silicon for crops: A review. *Agron Sustain Dev.* 2012;32:201–13. <https://doi.org/10.1007/s13593-011-0039-8>
- Liang Y, Sun W, Zhu YG, Christie P. Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. *Environ Pollut.* 2007;147(2):422–8. <https://doi.org/10.1016/j.envpol.2006.06.008>
- FAO, UNESCO. Soil map of the world. Vol. I: Legend. Paris: FAO-UNESCO; 1974.
- Gomez KA, Gomez AA. Statistical procedures for agricultural research. New York: John Wiley and Sons; 1991.
- Sudhagar Rao GB, Balachandrakumar V, Immanuel RR, Nambi J, Suthin Raj T. Influence of zinc and iron fortified micronutrients on the growth, yield and economics of rice (*Oryza sativa* L.). *Crop Res.* 2020;55(5–6):3. <https://doi.org/10.31830/2454-1761.2020.029>
- Singh V, Singh V, Singh S, Khanna R. Effect of zinc and silicon on growth and yield of aromatic rice (*Oryza sativa*). *J Rice Res Dev.* 2020;3(1):82–6. <https://doi.org/10.36959/973/424>
- Deepana P, Sathiyabama K, Santhya P, Sivasankari Devi T. Effect of seaweed extract on rice (*Oryza sativa* var. ADT 53) productivity and soil fertility in Cauvery delta zone of Tamil Nadu, India. *J Appl Nat Sci.* 2021;13(3):1111–20. <https://doi.org/10.31018/jans.v13i3.2906>
- Sandhya K, Prakash NB, Meunier JD. Diatomaceous earth as source of silicon on the growth and yield of rice in contrasted soils of Southern India. *J Soil Sci Plant Nutr.* 2018;18(2):344–60. <https://doi.org/10.4067/S0718-95162018005001201>
- Khan W, Rayirath UP, Subramanian S, Jithesh MN, Rayorath P, Hodges DM, et al. Seaweed extracts as biostimulants of plant growth and development. *J Plant Growth Regul.* 2009;28:386–99. <https://doi.org/10.1007/s00344-009-9103-x>
- Keshari PK, Laik R, Singh A, Sarkar S. Effect of zinc on growth, yield and zinc use efficiency of rice in rice-wheat cropping system. *Int J Plant Soil Sci.* 2019;29(1):1–8. <https://doi.org/10.9734/ijpss/2019/v29i130134>
- Bharathiraja P. Response of aerobic rice to silicon fertilization [MSc thesis]. Chidambaram: Annamalai University; 2014.
- Layek J, Das A, Idapuganti RG, Sarkar D, Ghosh A, Zedape ST, et al. Seaweed extract as organic bio-stimulant improves productivity and quality of rice in eastern Himalayas. *J Appl Phycol.* 2018;30:547–58. <https://doi.org/10.1007/s10811-017-1225-0>
- Pati S, Pal B, Badole S, Hazra GC, Mandal B. Effect of silicon fertilization on growth, yield and nutrient uptake of rice. *Commun Soil Sci Plant Anal.* 2016;47(3):284–90. <https://doi.org/10.1080/00103624.2015.1122797>
- Shamir Khan S, Basavaraja PK, Yogendra ND, Arup G. Influence of seaweed saps on germination, growth and yield of hybrid maize under Cauvery command of Karnataka, India. *Int J Curr Microbiol Appl Sci.* 2017;6(9):1047–56. <https://doi.org/10.20546/ijcmas.2017.609.126>
- Chandramani P, Rajendran R, Muthiah C, Chinniah C. Organic source induced silica on leaf folder, stem borer and gall midge population and rice yield. *J Biopestic.* 2010;3(2):423–7. <https://doi.org/10.57182/jbiopestic.3.2.423-427>
- Javvaji S, Telugu UM, Venkata RDB, Madhav MS, Rathod S, Chintalapati P. Characterization of resistance to rice leaf folder *Cnaphalocrocis medinalis* in mutant Samba Mahsuri rice lines. *Entomol Exp Appl.* 2021;169(9):859–75. <https://doi.org/10.1111/eea.13082>
- Rizwan M, Atta B, Rizwan M, Sabir AM, Tahir M, Sabar M. Silicon plays an effective role in integrated pest management against rice leaf folder *Cnaphalocrocis medinalis* Guenee (Lepidoptera: Pyralidae). *Pak J Zool.* 2021:1–7. <https://doi.org/10.17582/journal.pjz/20200330090344>
- Nayak P, Biswas S, Dutta D. Effect of seaweed extracts on growth, yield and economics of kharif rice (*Oryza sativa* L.). *J Pharmacogn Phytochem.* 2020;9(3):247–53. <https://doi.org/10.22271/phyto.2020.v9.i3d.11269>
- Afrin S, Anwar MDP, Rahman R, Hasan AK, Forhad FB, Yeasmin AKMS, et al. Comparative performance and economics of different zinc application approaches in Boro rice. *Fundam Appl Agric.* 2022;7(2):121–30. <https://doi.org/10.5455/faa.87165>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.