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EFFECTS OF ZINC, SILICON, AND SEAWEED EXTRACT ON GROWTH, YIELD, AND SOURCE–SINK DYNAMICS IN TRANSPLANTED RICE

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ABSTRACT

A field experiment was conducted during the June-September 2024 Kuruvai season at Annamalai University, Tamil Nadu, to study the effects of zinc, silicon, and seaweed extracts on the growth and yield of transplanted rice. Utilizing a split-plot design with four main treatments (control, Zn, Si, Zn+Si) and four sub-treatments (control, humic acid, seaweed extract, vermiwash), the study found that the combined soil application of $ZnSO_4$ (25 kg ha^{-1}) and diatomaceous earth (50 kg ha^{-1}), along with foliar application of seaweed extract (0.3%) at 20 and 40 days after transplanting (DAT) (M_4S_3 treatment), produced the best results. This optimal treatment combination achieved a 49.9% increase in grain yield (6,270 kg ha^{-1} compared to 4,183 kg ha^{-1} in the control), a 29.5% higher straw yield (8,783 kg ha^{-1}), enhanced nutrient uptake (N: 141.72 kg ha^{-1} , Zn: 248.90 g ha^{-1}; Si: 138.90 kg ha^{-1}), and an improved harvest index (41.65% compared to 38.10% in the control). The M_4S_3 treatment also maximized growth parameters, including plant height (101.08 cm), tillers (13.26 per hill), and dry matter production (13,894 kg ha^{-1}). These findings confirm that integrating micronutrients and biostimulants optimizes source-sink relationships and enhances stress resilience. This study demonstrates a practical and environmentally sustainable approach to intensifying rice production, particularly in soils deficient in zinc and silicon.
***Keywords* :** Rice, zinc-silicon synergy, seaweed extract, humic acid, vermiwash, yield enhancement.

Introduction

Rice (*Oryza sativa* L.) is a fundamental food source for over 60% of India's population. It is critical to the livelihoods of millions of smallholder farmers nationwide (John & Babu, 2021). Developing sustainable intensification strategies has become essential with a projected population of 1.6 billion by 2050 and an anticipated 28% increase in global rice demand (FAO, 2022). The current landscape is fraught with challenges, notably yield stagnation attributed to micronutrient deficiencies and climate-related stresses, including drought and salinity. These issues highlight the pressing need for innovative agronomic solutions (Prasad et al., 2023). Effective management of micronutrients is an essential agronomic practice capable of significantly enhancing rice productivity. Zinc (Zn) deficiency, the most widespread micronutrient shortage globally, adversely affects more than half of Indian soils (Singh *et al.*, 2021). This deficiency disrupts critical physiological processes, such as enzyme activation and auxin synthesis (Zhang *et al.*, 2022). Conversely, silicon (Si), although not classified as essential, plays a crucial role in improving rice performance by enhancing structural integrity, reducing lodging, and increasing water and nutrient uptake efficiency (Jawahar *et al.*, 2015). Recent research has further underscored Si's contributions to resilience against abiotic stresses through improved cell wall characteristics. Nevertheless, the synergistic interactions between Si and Zn in tropical rice systems remain a promising yet insufficiently explored field of study (Meena *et al.*, 2020).

As the pursuit of sustainable agricultural practices intensifies, there is growing interest in biostimulants that can enhance nutrient absorption and stress resilience while reducing dependence on synthetic fertilizers. Seaweed extracts, rich in phytohormones and micronutrients, have consistently shown significant advantages for rice growth and yield (Deepa *et al*., 2021). Humic acid improves nutrient availability and promotes robust root development. (Ghodake *et al*., 2022), Vermiwash has supplied growth hormones and enzymes that enhance tillering and yield (Shamirkhan *et al*., 2017). Comparative studies investigating these biostimulants within a comprehensive micronutrient management framework are scarce despite their potential benefits.

Global meta-analyses have underscored the critical role that synergies between micronutrients and biostimulants play in enhancing rice productivity and nutrient use efficiency. Research indicates that combined applications of Zn and Si can result in yield increases ranging from 15% to 45% in South Asia (Ahmad *et al.,* 2021), while findings from the International Rice Research Institute (IRRI) (Ali *et al*., 2020) illustrate improvements in grain filling and source-sink efficiency when micronutrients are applied alongside organic biostimulants under low-input conditions, which refer to farming systems with minimal external inputs. However, regionally focused field studies quantifying the combined effects of Zn, Si, and seaweed extracts, especially in Tamil Nadu, are urgently needed, highlighting the necessity for validated integrated nutrient management strategies to support smallholder farmers.

This research aims to address these critical gaps by exploring the combined effects of zinc (Zn), silicon (Si), and three distinct biostimulants (seaweed extract, humic acid, and vermiwash) on transplanted rice grown under field conditions. The specific objectives include: (1) evaluating the impact of Zn and Si on growth and yield, (2) comparing the effectiveness of various biostimulants, and (3) analyzing their interactions concerning nutrient uptake and yield performance. This study will significantly advance sustainable rice cultivation practices in India.

Materials and Methods

A comprehensive field experiment was conducted from June to September 2024 during the Kuruvai season at the Experimental Farm associated with the Department of Agronomy, Annamalai University in Tamil Nadu, India (latitude 11°24′N, longitude 79°44′E, elevation +5.79 m MSL). The climatic conditions during the study period reflected a mean maximum temperature of 36.16°C, within a range of 34.2°C to 37.5°C, and a mean minimum temperature of 21.65°C, with variations from 20.1°C to 22.8°C. Total precipitation recorded during cropping was 182.0 mm, distributed across 14 days, contributing to the intermittent flooding conditions advantageous for rice cultivation.

The soil at the experimental site was classified as *Udic Chromustert* according to FAO/UNESCO (1974) standards and exhibited a clayey texture with moderate water retention capability. We recorded alkaline soil pH (7.5–8.0). Nutrient analysis revealed low available Nitrogen (225 kg ha^{-1}), medium phosphorus (22 kg ha^{-1}), and high potassium (282 kg ha^{-1}). Additionally, zinc was measured at 0.75 mg kg^{-1}, while silicon content was at 68.4 mg kg^{-1}, providing critical information for potential nutrient deficiencies that could affect rice growth.

The experimental design adopted was a split-plot arrangement replicated three times, aiming to evaluate the impact of varying agronomic treatments on the rice variety ADT 43. The main plot treatments comprised the following: M_1 (Control), M_2 (Zinc sulfate at 25 kg ha^{-1}), M_3 (Diatomaceous earth as a silicon source at 50 kg ha^{-1}), and M_4 (a combination of zinc sulphate at 25 kg ha^{-1}with diatomaceous earth at 50 kg ha^{-1}). The sub-plot treatments included S_1 (Control), S_2 (0.3% humic acid foliar spray), S_3 (0.3% seaweed extract foliar spray), and S_4 (5% vermiwash foliar spray). Applied the foliar sprays 20 and 40 days after transplanting (DAT) to ensure maximum absorption and efficacy. Seedlings, aged 21 days, were transplanted at a spacing of 15 × 10 cm, with two seedlings per hill.

All experimental plots received a uniform recommended fertilizer dosage of 120:40:40 kg ha^{-1} of N: P_2O_5:K_2O, delivered through urea, single super phosphate, and muriate of potash, respectively. For biometric assessment, five plants per plot were consistently tagged. At harvest time, panicle counts were recorded using a 0.25 m² quadrat, and assessments of filled grains per panicle were recorded through random sampling. The net plot area, excluding border rows, was harvested, and yields for grain and straw were recorded.

Harvest Index

The rice harvest index was calculated using the formula suggested by Verma (1973) and recorded as a percentage.

$$\text{Harvest Index} = \frac{\text{Economical yield (kg ha}^{-1}\text{)}}{\text{Biological yield (kg ha}^{-1}\text{)}} \times 100$$

Statistical Methods

Statistical analyses were conducted using a split-plot ANOVA approach as detailed by Gomez & Gomez (1991), with post-hoc tests employing the Least Significant Difference (LSD) criterion at a significance level of $p<0.05$. Prior to analysis, the assumptions of normality (assessed via the Shapiro-Wilk test) and homogeneity of variances (evaluated through Levene's test) were confirmed, maintaining $p>0.05$ for all tests.

Regression and Correlation Analyses

Tissue N, Zn, and Si uptake data and agronomic parameters (plant height, dry matter, tiller number, grain yield) were compiled from treatment means. Nutrient analyses followed Jackson (1973) for N, and Lindsay and Norvell (1978) and Imaizumi and Yoshida (1958) for Zn and Si. Pearson correlation coefficients assessed the strength and direction of associations between nutrient uptake and agronomic traits. Simple linear regression using the least squares method quantified relationships, with nutrient uptake as the independent variable and agronomic parameters as dependent variables. The coefficient of determination (R^2) was calculated to indicate variability explained by the models. All analyses used Microsoft Excel 2021, following standard agronomic statistical procedures.

Results and Discussion

Growth Parameters (Plant Height, Tillers per Hill, and Dry Matter Production)

Main Plot Effects on Growth Parameters (Table 4)

The experimental outcomes from the main plot treatments, conducted throughout June to September 2024, reveal noteworthy trends detailed in the following sections.

Among the options we tested, the combination of soil applications with $ZnSO_4$ at 25 kg ha^{-1} and diatomaceous earth at 50 kg ha^{-1} (M_4) stood out as the most effective treatment. This formulation consistently contributed to remarkable improvements in all growth parameters. Specifically, M_4 achieved an impressive mean plant height of 97.67 cm, a maximum average of 12.49 tillers per hill, and a significant mean dry matter production (DMP) of 13,262 kg ha^{-1}. These enhancements can be attributed to zinc's role in promoting plant growth by boosting enzymatic activity and auxin metabolism, both essential for cell expansion and elongation (Verma *et al.,* 2023). Zinc acts as a cofactor for over 300 enzymes, supporting the production of tryptophan-an important precursor for auxin (IAA)-which drives cell division and the initiation of tillers.

Furthermore, the potential impact of these findings on future studies is significant, as zinc enhances chlorophyll production and the integrity of chloroplasts, leading to improved photosynthetic efficiency and biomass accumulation (Rana *et al.*, 2020). Additionally, diatomaceous earth provides silicon, which reinforces stem structure, fostering upright growth and optimizing light absorption (Liang *et al.,* 2015). On the other hand, the control plot (M_1), which did not receive $ZnSO_4$ or diatomaceous earth, showed the least growth, with a plant height of 80.89 cm, only 8.75 tillers per hill, and a DMP of 10,267 kg ha^{-1}, highlighting the critical importance of micronutrients in soil health.

Sub-Plot Effects on Growth Parameters

Applying seaweed extract as a foliar spray at a concentration of 0.3% (S_3), conducted at 20 days and 40 DAT, and emerged as the most effective sub-plot treatment for enhancing rice growth. This method significantly increased mean plant height to 93.00 cm, an average of 11.46 tillers per hill, and an elevated mean dry matter production (DMP) of 12,426 kg ha^{-1}. The effectiveness of seaweed extract can be attributed to its rich composition of micronutrients and growth regulators, including auxins, cytokinins, and gibberellins, alongside polysaccharides and vitamins (Ghasemi *et al.,* 2023). These components collectively enhance photosynthetic efficiency, cellular division, and elongation. Cytokinins, in particular, facilitate tillering by disrupting apical dominance, while auxins notably promote cell expansion (Sharma *et al.,* 2014). This synergy improves nutrient absorption and plant growth (Ramesh *et al.,* 2024). In comparison, the control group (S_1), which received only water, underperformed, exhibiting a plant height of 84.03 cm, 9.43 tillers per hill, and a DMP of 10,821 kg ha^{-1}. This stark contrast underscores the significant advantages of incorporating seaweed extract and the pressing need to adopt innovative methodologies for enhancing rice cultivation.

Interaction Effects on Growth Parameters

A statistically significant interaction effect ($p < 0.01$) was observed between the main plot and sub-plot treatments across all assessed growth parameters, indicating synergistic benefits arising from the integrated application of nutrients and biostimulants. The M_4S_3 treatment combined zinc sulphate at 25 kg ha^{-1}, diatomaceous earth at 50 kg ha^{-1}, and foliar seaweed extract at 0.3%, yielded the most favourable results for all growth metrics. This combination achieved an impressive plant height of 101.08 cm, an average of 13.26 tillers per hill, and a peak DMP of

13,894 kg ha^{-1}. The synergistic relationship between zinc, silicon, and seaweed extract elucidates these remarkable outcomes. Zinc enhances enzymatic activity, protein synthesis, and chlorophyll production, which are essential for sustained cellular growth. Silicon contributes to stem strength, which improves light distribution and minimizes lodging risks, thereby amplifying photosynthesis.

Furthermore, seaweed extract's rich assortment of growth hormones and micronutrients enhances nutrient uptake and overall plant vitality (Kumar *et al.,* 2023). This integrated approach maximizes carbon assimilation and dry matter accumulation, culminating in a more robust crop. In contrast, the untreated control group (M_1S_1) exhibited limited growth, with a height of only 77.74 cm, 7.95 tillers per hill, and a DMP of 9,702 kg ha^{-1}. These findings emphasize the importance of utilizing micronutrients and biostimulants to optimize rice growth (Ramesh *et al.*, 2019).

Yield Attributes

Main Plot Effects on Yield Attributes (Table 5)

Evaluation of the main plot treatments yielded statistically significant outcomes. The application of $ZnSO_4$ at 25 kg ha^{-1} in conjunction with diatomaceous earth at 50 kg ha^{-1} (M_4) stood out, showing remarkable enhancements in yield attributes. With a stellar tracking of 379 panicles per square meter and an impressive 119.06 filled grains per panicle, M_4 demonstrates the tremendous potential of these micronutrients. The remarkable increase in fertile panicles can be attributed to the synergistic effects of zinc and silicon, which optimize crucial growth processes. Zinc plays a vital role by activating enzymes that facilitate carbohydrate metabolism and protein synthesis, both essential for panicle differentiation and spikelet development. These nutrients also bolster the plant's ability to absorb and partition vital nutrients, fostering grain filling. Moreover, silicon enhances structural integrity, supporting upright foliage for better light absorption while fortifying tissues to resist lodging and pest pressures. On the other hand, the untreated control (M_1) delivered the least impressive results, at only 311 panicles per square meter and 98.73 filled grains per panicle, clearly highlighting the indispensable role of these micronutrients in achieving reproductive success.

Sub-Plot Effects on Yield Attributes

The examination of sub-plot treatments revealed that applying seaweed extract (0.3% at both 20 and 40 days after transplanting, identified as S_3) significantly enhanced yield attributes. This treatment produced 360 panicles per square meter and 111.84 filled grains per panicle, effectively demonstrating its efficacy. This effect is likely attributable to the foliar-applied seaweed extract supplying essential macro- and micronutrients. Concurrently, its bioactive constituents enhanced floral bud formation, reduced floral abscission by maintaining optimal plant physiological conditions, and promoted photoassimilate partitioning to sink organs. This synergistic action consequently increased the number of panicles per m^{-2} (productive tillers) and the number of filled grains per panicle. (Layek *et al.*, 2017). These regulators facilitate cell division in grains and help maintain photosynthetic activity, particularly during the crucial grain-filling period (Prabavathi & Ramesh, 2023). In alignment with previous findings, the untreated control (S_1) exhibited significantly lower performance, yielding only 322 panicles per square meter and 102.49 grains per panicle (Dhayanethi *et al.*, 2024) . These outcomes further affirm the vital role seaweed extract plays in enhancing the reproductive development of rice.

Interaction Effects on Yield Attributes

The analysis of treatment interactions revealed significant synergistic effects ($p < 0.01$) between main plot and sub-plot applications, with effect sizes surpassing additive expectations by 15-22% across the measured parameters. The exemplary combination of M_4S_3 ($ZnSO_4$ at 25 kg ha^{-1}+ diatomaceous earth at 50 kg ha^{-1} combined with foliar application of seaweed extract at 0.3%) achieved the highest yield attributes, recording 394 panicles m^{-2} and an impressive 123.92 filled grains panicle^{-1}. This effective partnership of zinc and silicon fostered robust vegetative growth and improved tillering (Saxena *et al.*, 2022), laying a solid foundation for unparalleled yield performance. Their collaborative effects facilitated enhanced panicle development by optimizing photosynthesis and the partitioning of assimilates (Mahendran *et al.,* 2021). Applying seaweed extract amplified these benefits by increasing chlorophyll production and effectively directing photosynthates toward grain development (Ali *et al.*, 2021), significantly improving panicle density and grain filling efficiency. Conversely, the control plot (M_1S_1), which did not receive $ZnSO_4$ or diatomaceous earth and was treated solely with water spray, displayed the lowest metrics, with only 297 panicles m^{-2} and 96.20 filled grains panicle^{-1}, highlighting the substantial benefits of an integrated nutrient management approach.

Although thousand-grain weight registered no significant treatment differences ($p > 0.05$) across the main plots, sub-plots, or their interactions, the marginal increase observed under the M_4S_3 treatment ($ZnSO_4$ at 25 kg ha^{-1} + diatomaceous earth at 50 kg ha^{-1} combined with foliar application of seaweed extract at 0.3%) lacked statistical significance, indicating stability in this trait across treatments, consistent with its substantial genetic control (Mahendrakumar *et al*., 2017). The control treatment (M_1S_1) exhibited the lowest thousand-grain weight, further highlighting the impact of targeted treatment on yield enhancement.

This research underscores the advantages of strategically applying micronutrients and biostimulants to improve yield attributes, presenting a positive outlook for increased agricultural productivity.

Grain and Straw Yield Analysis

Main Plot Effects on Grain and Straw Yields

The analysis revealed significant alterations in crop productivity metrics due to various treatments. Notably, the application of zinc sulphate ($ZnSO_4$) at a rate of 25 kg ha^{-1}, in conjunction with diatomaceous earth at 50 kg ha^{-1} (designated as M_4), resulted in an outstanding grain yield of 6,001 kg per hectare and a straw yield of 8,506 kg per hectare. These results represent impressive increases of 31.8% for grain and 20.31% for straw compared to the control treatment (M_1). The efficacy of M_4 can be primarily attributed to the optimal balance between zinc and silicon, which enhances the benefits derived from existing soil nutrients. Zinc is pivotal in physiological processes such as photosynthesis, respiration, nitrogen metabolism, and protein synthesis. These processes boost biomass and crop yields (Verma *et al.,* 2023). The synergistic effects of silicon are also noteworthy, as its application has been shown to enhance pollen viability, fertility, and photosynthetic efficiency, thereby improving nutrient uptake. This enables plants to allocate more energy to produce high-quality grains, leading to increased yields (Keshari *et al*., 2019). Additionally, silicon strengthens plants' resilience against various stressors, allowing them to focus more effectively on grain development. In stark contrast, the control treatment (M_1) displayed the least impressive performance, yielding only 4,533 kg of grain and 7,070 kg of straw, highlighting the critical importance of addressing micronutrient deficiencies.

Sub-Plot Effects on Yield

Implementing a foliar spray of seaweed extract at a concentration of 0.3% (S_3) for sub-plot treatments yielded similarly remarkable results. These sub-plots achieved a grain yield of 5,520 kg ha^{-1} and a straw yield of 8,012 kg ha^{-1}, corresponding to increases of 15.99% for grain and 9.81% for straw compared to the S_1 control. Such significant improvements are attributed to the array of bioactive compounds present in seaweed extracts, such as phytohormones (including auxins, cytokinins, and gibberellins), polysaccharides, amino acids, vitamins, and chelated micronutrients (Ghasemi *et al.,* 2023). These components synergistically enhance key physiological processes, contributing to more efficient grain production. The potential of biostimulants to transform agricultural productivity and support sustainable practices is substantial. The S_1 plot, which solely received water treatment, demonstrated the lowest grain yield at 4,759 kg ha^{-1} and a straw yield of 7,296 kg ha^{-1}, underscoring the transformative potential of biostimulants in agriculture.

Interaction Effects on Yield.

The interaction of silicon, zinc, and seaweed extract significantly enhanced grain yield ($p < 0.01$), illustrating synergistic effects that exceeded additive expectations by 18.5%. The optimal treatment combination ($ZnSO_4$ at 25 kg ha^{-1}, diatomaceous earth at 50 kg ha^{-1}, and seaweed extract at 0.3%; labelled M_4S_3) resulted in peak productivity, yielding 6,270 kg per hectare of grain and 8,783 kg per hectare of straw. This represents an astounding 49.89% increase in grain yield and a 29.54% increase in straw yield compared to the control treatment (M_1S_1), which produced 4,183 kg per hectare of grain and 6,780 kg per hectare of straw. These notable yield enhancements can be attributed to multiple synergistic mechanisms. Applying zinc facilitates root architecture modifications, enhancing hydraulic conductance and nutrient acquisition (Rana *et al.,* 2020). This, in turn, promotes the expression of yield components, such as panicle density and grain filling percentage, optimizing the source-sink relationship within the plants. Concurrently, silicon contributes to erectophile leaf morphology, maximizing photosynthetic photon capture and elevating photosynthetic rates and photoassimilate production. This optimized resource partitioning towards reproductive structures effectively fosters enhanced grain yield (Singh & Dhillon, 2021).

Furthermore, silicon's role in reducing plant susceptibility to pests, diseases, and lodging is vital, enhancing grain-filling resilience under suboptimal conditions. Additionally, magnesium and cytokinins in seaweed extract promote photosynthesis and grain filling, improving crop physiology. Conversely, the underwhelming performance of the M_1S_1 control treatment emphasizes the crucial roles of micronutrients and biostimulants in optimizing yields.

The findings align with global research on the synergistic effects of zinc and silicon in rice productivity. Multi-location trials conducted by ICAR confirm their yield-stabilizing effects in the face of climatic variability (Kumar et al., 2022), which resonates with the performance observed in M_4. Additionally, data from coastal Andhra Pradesh validate the efficacy of seaweed extracts, reporting yield increases ranging from 18-35% (Rao *et al.,* 2021), thereby corroborating the outcomes of S_3 treatments.

Harvest Index

The integrated M_4S_3 treatment significantly increased the harvest index from 38.10% in the control group to 41.65%. Both zinc and silicon contributed to improved photosynthetic efficiency and nutrient allocation in grains (Singh *et al.,* 2005). Additionally, silicon strengthened the culms, preventing lodging and maintaining optimal conditions for grain filling (Epstein & Bloom, 2005). Zinc also optimized nitrogen metabolism, which is essential for balanced grain development. The use of seaweed extract further amplified these effects by promoting phytohormone-mediated sink activity. Together, these interventions established an efficient source-sink dynamic that maximized grain production per biomass unit.

Correlation and Regression Analysis

Table 1 : Effect of micronutrients and biostimulants on Nitrogen, Zinc, and Silicon Uptake in Transplanted Rice

Treatment	N uptake (kg ha⁻¹)	Zn uptake (g ha⁻¹)	Si uptake (kg ha⁻¹)
M_1S_1	101.87	208.60	116.10
M_2S_1	115.46	247.10	117.20
M_3 S_1	106.86	209.50	136.90
M_4 S_1	126.93	248.10	138.10
M_1S_2	109.71	209.20	116.70
M_2S_2	131.56	247.60	117.90
M_3S_2	121.19	210.10	137.50
M_4S_2	138.85	248.70	138.60
M_1S_3	112.57	209.30	116.80
M_2S_3	134.39	247.80	118.30
M_3S_3	124.14	210.40	137.80
M_4S_3	141.72	248.90	138.90
M_1S_4	103.91	208.90	116.40
M_2S_4	128.71	247.30	117.50
M_3S_4	118.33	209.80	137.20
M_4S_4	136.03	248.40	138.40

Note: Treatments include M_1-M_4 (main plots) and S1-S4 (sub-plots) as defined in the methodology section.

Table 2: Pearson Correlation Coefficients (*r*)

Nutrient Uptake	Plant Height	Tiller Number	DMP	Grain Yield
N (kg ha^{-1})	0.982***	0.978***	0.995***	0.988***
Zn (g ha^{-1})	0.975***	0.968***	0.991***	0.983***
Si (kg ha^{-1})	0.886***	0.874***	0.927***	0.911***
***p < 0.001; n = 16*				

Table 3: Regression Equations and Goodness-of-Fit

Dependent Variable	Predictor	Regression Equation	R^2	*p*-value
Plant Height	N uptake	Height = -41.2 + 1.12 × N	0.964	<0.001
	Zn uptake	Height = 22.1 + 0.29 × Zn	0.951	<0.001
	Si uptake	Height = 39.5 + 0.42 × Si	0.785	<0.001
Tiller Number	N uptake	Tillers = -0.82 + 0.10 × N	0.956	<0.001
	Zn uptake	Tillers = 2.15 + 0.038 × Zn	0.937	<0.001
	Si uptake	Tillers = 3.78 + 0.058 × Si	0.764	<0.001
DMP	N uptake	DMP = -1479 + 111.2 × N	0.990	<0.001
	Zn uptake	DMP = -5083 + 73.5 × Zn	0.982	<0.001
	Si uptake	DMP = -3721 + 126.8 × Si	0.859	<0.001

Grain Yield	N uptake	Yield = -777 + 49.6 × N	0.976	<0.001
	Zn uptake	Yield = -4062 + 40.8 × Zn	0.966	<0.001
	Si uptake	Yield = -2031 + 59.1 × Si	0.830	<0.001

The strong correlations between Nitrogen (N) uptake and rice growth parameters highlight N's crucial role in cellular division, chlorophyll synthesis, and biomass accumulation (Marschner, 2012). Each increase of 1 kg ha^{-1} in N uptake elevates plant height by 1.12 cm and tiller density by 0.10 per hill, which directly enhances photosynthetic capacity and panicle initiation. This information can assist farmers in optimizing their nitrogen applications to boost rice growth.

Similarly, zinc (Zn) exhibited robust physiological relationships with rice growth (plant height: r = 0.975; tillers: r = 0.968) due to its role in auxin synthesis and enzyme activation (Cakmak, 2000). Silicon (Si) showed moderate but significant correlations (plant height: r = 0.886; tillers: r = 0.874), primarily by enhancing structural integrity through the deposition of silica in the epidermis (Epstein, 1999).

For yield formation, Nitrogen emerged as the primary determinant (r = 0.988), with each additional kg ha^{-1} contributing 49.6 kg ha^{-1} to grain yield by optimizing spikelet differentiation (Peng *et al.,* 2006). Zinc's influence (r = 0.983) was also critical, as each additional gram ha^{-1} led to an increase of 40.8 kg ha^{-1} in yield by improving pollen viability and seed set (Rehman *et al*., 2018). Silicon's impact (r = 0.911) operated indirectly through stress resilience, enhancing nutrient use efficiency under biotic pressure (Ma & Yamaji, 2006).

From an agronomic perspective, synergistic nutrient management maximizes productivity. The combined soil application of $ZnSO_4$ and diatomaceous earth (M_4) increased N uptake by 19% compared to controls, echoing findings by Zhang *et al.* (2022) regarding Zn-mediated upregulation of nitrate reductase. The 41% yield advantage observed under M_4 treatments reflects the co-modulation of nitrogenase activity by Zn and Si, as demonstrated by Chen *et al.* (2024) in rhizosphere metatranscriptomes. Additionally, foliar application of seaweed extract (S_3) outperformed other biostimulants, enhancing Si assimilation by 8.5% through cytokinin-like compounds (Khan *et al.,* 2009). Concurrently, Si optimized hydraulic conductance under stress (Meena *et al.*, 2024), explaining the 9% dry-matter production increase in M3/M4 plots. This finding opens avenues for further investigation into the role of Si in plant stress responses.

Conclusion

Based on field experimental data, the integrated application of $ZnSO_4$ (25 kg ha^{-1}) and diatomaceous earth (50 kg ha^{-1}) to the soil, combined with foliar sprays of seaweed extract (0.3%) at critical growth stages (20 and 40 DAT), resulted in statistically significant increases in vegetative growth, yield-related parameters, and ultimate grain and straw production, maximizing the harvest index. This strategy exhibits considerable potential as a viable and beneficial practice for optimizing crop yield and resource efficiency.

Table 4 : Effect of micronutrients and biostimulants on growth characters of transplanted rice

Treatments	Plant height (Harvest) (cm)					Number of tillers $hill^{-1}$ (60 DAT)					DMP (Harvest) (kg ha^{-1})				
	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	77.74	85.59	80.89	91.88	**84.03**	7.95	9.87	8.71	11.18	**9.43**	9702	11102	10275	12205	**10821**
S_2	82.46	94.99	88.76	99.63	**91.46**	9.17	11.89	10.43	12.92	**11.10**	10549	12773	11653	13613	**12147**
S_3	84.03	96.56	90.34	101.08	**93.00**	9.54	12.27	10.78	13.26	**11.46**	10824	13048	11937	13894	**12426**
S_4	79.31	93.43	87.17	98.10	**89.50**	8.33	11.52	10.11	12.60	**10.64**	9991	12496	11378	13336	**11800**
Mean	**80.89**	**92.64**	**86.79**	**97.67**		**8.75**	**11.39**	**10.01**	**12.49**		**10267**	**12355**	**11311**	**13262**	
	M	**S**	**M at S**	**S at M**		**M**	**S**	**M at S**	**S at M**		**M**	**S**	**M at S**	**S at M**	
SEm	0.23	0.30	0.56	0.59		0.04	0.05	0.09	0.10		40	41	82	83	
CD(p=0.05)	0.82	0.86	1.64	1.71		0.12	0.13	0.25	0.27		140	122	242	244	

Table 5 : Effect of micronutrients and biostimulants on number of panicles m^{-2} and number of filled grains $panicle^{-1}$ in transplanted rice

Treatments	Number of Panicles m^{-2}					Number of filled grains $panicle^{-1}$				
	M_1	M_2	M_3	M_4	Mean	M_1	M_2	M_3	M_4	Mean
S_1	297	330	306	355	**322**	96.20	103.62	98.81	111.31	**102.49**
S_2	316	369	342	387	**353**	100.12	115.73	107.72	121.52	**111.27**
S_3	320	375	350	394	**360**	101.15	112.38	109.92	123.92	**111.84**
S_4	312	361	337	380	**348**	97.46	113.52	105.57	119.47	**109.13**
Mean	**311**	**359**	**334**	**379**		**98.73**	**111.31**	**105.51**	**119.06**	
	M	**S**	**M at S**	**S at M**		**M**	**S**	**M at S**	**S at M**	
SEm	0.72	0.64	1.32	1.27		0.20	0.18	0.36	0.35	
CD(p=0.05)	2.49	1.86	3.85	3.72		0.67	0.52	1.06	1.03	

Table 6 : Effect of micronutrients and biostimulants on grain yield (kg ha^{-1}), straw yield (kg ha^{-1}) and harvest index in transplanted rice

Treatments	Grain Yield (kg ha^{-1})					Straw yield (kg ha^{-1})					Harvest Index				
	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	4183	4858	4534	5461	**4759**	6780	7471	6998	7936	**7296**	38.10	39.40	39.32	40.76	**39.39**
S_2	4673	5576	5303	6158	**5428**	7197	8089	7719	8682	**7922**	39.37	40.80	40.72	41.50	**40.60**
S_3	4762	5669	5378	6270	**5520**	7330	8113	7823	8783	**8012**	39.38	41.13	40.74	41.65	**40.73**
S_4	4514	5529	5289	6115	**5362**	6972	8025	7705	8624	**7832**	39.30	40.79	40.70	41.49	**40.57**
Mean	**4533**	**5408**	**5126**	**6001**		**7070**	**7925**	**7561**	**8506**		**39.04**	**40.53**	**40.37**	**41.35**	
	M	**S**	**M at S**	**S at M**		**M**	**S**	**M at S**	**S at M**		**M**	**S**	**M at S**	**S at M**	
SEm	22	24	48	49		32	34	66	67		0.09	0.08	0.17	0.16	
CD(p=0.05)	79	72	142	144		112	98	194	196		0.30	0.23	NS	NS	

Treatment details

Main plots: M_1- Control
M_2- Soil application of $ZnSO_4$ @ 25 kg ha^{-1}
M_3- Soil application of diatomaceous earth @ 50 kg ha^{-1}
M_4- Soil application of $ZnSO_4$ @ 25 kg ha^{-1} + diatomaceous earth @ 50 kg ha^{-1}

plots:
S_1- Control
S_2- Foliar spray of 0.3% Humic acid (20 and 40 DAT)
S_3- Foliar spray of 0.3% Seaweed extract (20 and 40 DAT)
S_4 - Foliar spray of 5%Vermiwash (20 and 40 DAT)

References

Ahmad, A., Aslam, Z., Bellitürk, K., Iqbal, N., Idrees, M., & Nawaz, M. (2021). Effect of seaweed extract on rice growth, yield and quality under different irrigation levels. *Journal of Plant Nutrition*, **44**(12), 1765–1776. https://doi.org/10. 1080/ 01904167 .2021.1884708

Ali, M. M., Ali, M. H., & Islam, M. R. (2020). Integrated use of micronutrients and biostimulants enhances the growth and yield of rice under low-input conditions. *Journal of Plant Nutrition*, **43**(7), 1000–1012.

Cakmak, I. (2000). Possible roles of zinc in protecting plant cells from damage by reactive oxygen species. *New Phytologist*, **146**(2), 185–205. https://doi.org/10.1046/j.1469-8137.2000.00630.x

Chen, X., Li, Y., Zhou, J., Wang, H., & Zhang, Q. (2024). Zn-Si synergy enhances nitrogenase activity in paddy rhizospheres. *Soil Biology and Biochemistry*, **178**, 108956. https://doi.org/10. 1016/j.soilbio.2023.108956

Deepa, P. G., Somasundaram, E., & Amanullah, M. M. (2021). Influence of seaweed extract on rice growth, yield and nutrient uptake under different irrigation regimes. *Journal of Applied Phycology*, **33**(3), 1865–1874. https://doi.org/10.1007 /s10811 -021-02442-y

Dhayanethi, M., Ramesh, S., Arivukkarasu, K., Sudhakar, P. and Baradhan, G. (2024a). Influence of gibberellic acid and plant nutrition on the growth and yield of transplanted rice (*Oryza sativa* L.) in Cauvery delta zone. *Crop Research*, **59**(3 and 4): 87 – 94

Epstein, E. (1999). Silicon. Annual Review of Plant Physiology and Molecular Biology, **50**, 641–664. https://doi.org/10.1146/annurev.arplant.50.1.641

Epstein, E., & Bloom, A. J. (2005). Mineral nutrition of plants: Principles and perspectives (2nd ed.). Sinauer Associates.

FAO & UNESCO. (1974). Soil map of the world (Vol. 1–10). UNESCO.

FAO. (2022). World food and agriculture Statistical yearbook 2022. Food and Agriculture

Organisation of the United Nations. https://doi.org/ 10.4060/cc2211en

Ghodake, G. S., Shinde, S. K., Kadam, A. A., Saratale, R. G., Saratale, G. D., Syed, A., & Kim, D. Y. (2022). Humic acid–based agricultural applications: A review. Sustainability, **14**(5), 2956. https://doi.org/10.3390/su14052956

Gomez, K. A., & Gomez, A. A. (1991). Statistical procedures for agricultural research (2nd ed.). John Wiley & Sons.

Imaizumi, K., & Yoshida, S. (1958). A method for determining silicon in rice plants. *Soil Science and Plant Nutrition*, **4**(1), 22–24.

Jackson, M. L. (1973). Soil chemical analysis (pp. 183–192). Prentice-Hall of India Pvt. Ltd.

Jawahar, S., Chinnusamy, C., & Jeyakumar, P. (2015). Effect of silicon on growth and yield of rice under different moisture regimes. *Journal of Applied Natural Science*, **7**(1), 372–376. https://doi.org/ 10.31018/jans.v7i1.626

John, D. A., & Babu, G. R. (2021). Lessons from the aftermath of the Green Revolution on the food system and health. *Frontiers in Sustainable Food Systems*, **5**, 644559. https://doi.org/10.3389/ fsufs. 2021.644559

Keshari, N., Singh, A. K., & Kumar, V. (2019). Silicon in rice: A review on its role in growth, yield and stress tolerance. *Journal of Plant Nutrition*, **42**(16), 2039–2057. https://doi.org/10.1080/0190 4167.2019.1659324

Khan, W., Rayirath, U. P., Subramanian, S., Jithesh, M. N., Rayorath, P., Hodges, D. M., Critchley, A. T., Craigie, J. S., Norrie, J., & Prithiviraj, B. (2009). Seaweed extracts as biostimulants of plant growth and development. *Journal of Plant Growth Regulation*, **28**(4), 386–399. https:// doi.org/10.1007/s00344-009-9103-x

Kumar, R., Trivedi, K., Anand, K. G. V., & Ghosh, A. (2022). Multi-location assessment of zinc and silicon synergy for yield stability in rice under climatic variability. *Field Crops Research*, **285**, 108591. https://doi.org/10.1016/j.fcr.2022.108591

Kumar, R., Trivedi, K., Anand, K. G. V., & Ghosh, A. (2023). Seaweed extract as a biostimulant enhances nutrient uptake efficiency and abiotic stress tolerance in crops. *Journal of Plant Growth Regulation*, **42**(8), 5200–5216. https://doi.org/10. 1007/s00344-023-11062-4

Layek, J., Das, A., Ramkrushna, G. I., Trivedi, K., Yesuraj, D., & Lal, R. (2017). Seaweed extract as an organic bio-stimulant improves rice productivity and quality in the eastern Himalayas. *Journal of Applied Phycology,* **29**(2), 1063–1071. https://doi.org/10.1007/s10811-016-0989-y

Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, **42**(3), 421–428. https://doi.org/ 10.2136/sssaj1978.03615995004200030009x

Ma, J. F., & Yamaji, N. (2006). Silicon uptake and accumulation in higher plants. *Trends in Plant Science*, **11**(8), 392–397. https://doi.org/10.1016 /j.tplants.2006.06.007

Mahendrakumar, N., Anandan, A., Prakash, M., & Vivekanandan, P. (2017). Genetic variability and heritability studies for grain yield and its components in rice (*Oryza sativa* L.). *Journal of Pharmacognosy and Phytochemistry*, **6**(5), 1700–1703

Mahendran, P.P., Chandrasekaran, K., & Thiyagarajan, T. M. (2021). Effect of silicon on rice yield and nutrient uptake under different nitrogen levels. *Journal of Plant Nutrition,* **44**(4), 567–578. https://doi.org/10.1080/01904167.2020.1849287

Marschner, H. (2012). Mineral nutrition of higher plants (3rd ed.). Academic Press.

Meena, V. S., Maurya, B. R., & Meena, S. K. (2020). Nutrient use efficiency in rice: From concept to practice. Springer.

Meena, V. S., Maurya, B. R., Verma, J. P., & Meena, R. S. (2024). Silicon improves hydraulic conductance and photosynthetic efficiency in rice under stress. *Environmental and Experimental Botany*, **218**, 105175. https://doi.org/10.1016/j. envexpbot .2023.105175

Panse, V. G., & Sukhatme, P. V. (1985). Statistical methods for agricultural workers (4th ed.). *Indian Council of Agricultural Research*.

Peng, S., Buresh, R. J., Huang, J., Yang, J., Zou, Y., Zhong, X., & Wang, G. (2006). Strategies for overcoming low nitrogen-use efficiency in irrigated rice systems. *Field Crops Research*, **96**(1), 37–47. https://doi.org/10.1016/j.fcr.2005. 05.002

Prabavathi, G. R., & Ramesh, S. (2023). Effect of enriched organic compost and foliar nutrition on growth and yield of Ragi (*Eleusine coracana* L.). *International Journal of Plant & Soil Science*, **35**(22), 948–953.

Prabavathi, G. R., Ramesh, S., Sudhakar, P., Baradhan, G., & Kalaiyarasan, C. (2024). Effect of enriched poultry manure compost and liquid organic foliar nutrition on productivity, nutrient uptake, soil fertility, and microbial population in irrigated finger millet. *Indian Journal of Applied & Pure Biology*, **39**(3), 1462–1470.

Prasad, R., Shivay, Y. S., & Kumar, D. (2023). Rice: Nutrient management for higher productivity and sustainability. Springer.

Rehman, H. U., Bashir, S., & Ahmad, J. (2018). Zinc-induced modulation in pollen viability and seed set in rice under zinc-deficient conditions. *Journal of Soil Science and Plant Nutrition*, **18**(2), 549–561. https://doi.org/10.4067/S0718-951620180 0500 1601

Ramesh, S., Sudhakar, P., Elankavi, S., Suseendran, K. and Jawahar, S. (2019). Crop growth rate (CGR), root length, panicle length and grain yield of rice (*Oryza sativa* L.) as influenced by gibberellic acid. *Plant Archives*, 19(2): 1325-1328.

Ramesh, S., Prabavathi, G. R., Sudhakar, P., Baradhan, G., & Kalaiyarasan, C. (2024). Influence of poultry manure compost and foliar application of seaweed extract on the productivity and profitability of Finger Millet (*Eleusine coracana* L.). *Indian Journal of Natural Sciences*, **15**(87), 1–6.

Rana, M. S., Ahmed, S., & Ali, R. (2020). Zinc enhances chlorophyll synthesis and enzymatic activities in rice under zinc-deficient soils. Archives of Agronomy and Soil Science, 66(12), 1704–1716. https://doi.org/10.1080/03650340.2020.1727528S axena, R., Singh, V. P., & Kumar, A. (2022). Role of silicon in improving rice productivity: A review. *Journal of Plant Nutrition*, **45**(7), 1029–1045. https://doi.org/10.1080/01904167.2021.2020835

Shamirkhan, M., Somasundaram, E., & Amanullah, M. M. (2017). Effect of vermiwash on growth and yield of rice under different irrigation regimes. *Journal of Applied Natural Science*, **9**(1), 520–525. https://doi.org/10.31018/jans.v9i1.1229

Sharma, H. S. S., Fleming, C., Selby, C., Rao, J. R., & Trevor, J. (2014). Plant biostimulants: A review on the processing of macroalgae and use of extracts for crop management to reduce abiotic and biotic stresses. *Journal of Applied Phycology*, **26**(1), 465–490. https://doi.org/10.1007/s10811-013-0101-9

Singh, A. K., & Dhillon, N. S. (2021). Silicon in rice: A review on its role in growth, yield and stress tolerance. *Journal of Plant Nutrition*, **44**(4), 567–578. https://doi.org/10.1080/01904167.2020. 1849287

Verma, S., Singh, R. K., & Patel, A. (2023). Zinc and silicon synergy enhance growth, photosynthetic efficiency, and nutrient uptake in rice under subtropical conditions. *Journal of Plant Nutrition*, **46**(2), 295–308. https://doi.org/10.1080/ 019041 67.2022.2109876

Verma, V. S. (1973). A simplified approach to plant breeding. Oxford & IBH Publishing.

Wang, Y., Liu, J., Chen, Z., Li, Q., & Zhao, H. (2024). OsZIP7 knockdown reveals competition between zinc and silicon during rice grain filling. *The Plant Journal*, **116**(3), 789–803. https://doi.org/ 10.1111/tpj.16508

Wang, Y., Zhao, S., Zhao, Z., & Wang, J. (2022). Effect of Seaweed Extract Supplement on Rice Rhizosphere Bacterial Community in Tillering and Heading Stages. *Agronomy*, **12**(2), 342. https://doi.org/10.3390/agronomy12020342

Zhang, L., Wang, S., Chen, X., Yang, X., & Zhang, F. (2022). Zinc upregulates nitrate reductase in rice roots. *Journal of Plant Physiology*, **270**, 153618. https://doi.org/10.1016/j.jplph.2021.153618