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RESEARCH ARTICLE

Synergistic effects of seaweed extract presoaking and foliar spray on the performance of paddy improved kavuni (CO 57)

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Abstract

Rice (*Oryza sativa* L.) is a staple food crop and a primary source of sustenance for more than half of the world's population. Seed treatments and foliar applications have emerged as effective methods to enhance growth and yield attributes. In this study, improved kavuni (CO 57) seeds were used for a field experiment conducted during the Samba season (2023). The experiment was designed using a Factorial Randomized Block Design with 15 treatments and three replications, focusing on foliar spray applications. The primary objective was to evaluate the impact of *Sargassum myricocystum, Kappaphycus alvarezii* methanol extract and foliar spray on rice growth and productivity. The results revealed that the combined application of presoaking seeds in 0.5 % *Sargassum myricocystum* methanol extract with a foliar spray of 2.5 % seaweed extract at the panicle initiation and flowering stages (T_1F_2) significantly enhanced plant growth and yield parameters. Higher plant height (121 cm), leaf area index (4.85), dry matter production (5180 kg ha^{-1}), productive tillers (281 m^{-2}), filled seeds per panicle (170), 1000 seed weight (22.34 g), seed yield (4552 kg ha^{-1}) and straw yield (6370 kg ha^{-1}) were recorded under T_1F_2 compared to other treatments. The use of organic input seaweed extracts, improved plant quality and yield sustainably without harming the natural ecosystem. This study highlights the significant potential of seaweed extracts in enhancing overall crop performance, leading to optimal plant growth characteristics and yield attributes. The findings emphasise the role of organic inputs in promoting sustainable agriculture, contributing to environmental conservation while supporting food security.

Keywords

paddy; presoaking; seaweed; *Sargassum myricocystum*; foliar; improved kavuni (CO 57)

Introduction

Rice (*Oryza sativa* L.) is a critical source of energy, proteins, and micronutrients for billions, especially in Asia, Africa, and Latin America. Rice is one of the most widely cultivated crops globally, serving as the staple diet for over 50 % of the population. As the demand for rice continues to grow with the burgeoning global population, efforts to enhance its productivity, quality, and sustainability have gained momentum. Among various rice varieties, pigmented rice, such as Kavuni, is highly regarded for its rich nutritional profile, making it a subject of increasing interest in both traditional and commercial agriculture (1, 2).

Pigmented rice varieties like Kavuni are unique because of their anthocyanin-rich bran layer, which gives them their distinctive colour and health benefits. These varieties are not only nutritionally superior but also hold potential therapeutic properties, including antioxidant, anti-inflammatory, and anti-carcinogenic effects (3). However, traditional cultivars often exhibit lower yield potential compared to modern high-yielding varieties. Addressing this gap, the improved kavuni (CO 57) has been developed to combine the nutritional advantages of pigmented rice with the agronomic benefits of higher yields and better adaptability to varied cultivable conditions (4).

The intensification of agriculture to meet global food demands has led to significant challenges, including soil degradation, overuse of chemical inputs, and declining biodiversity. These factors have resulted in diminishing returns, environmental degradation, and reduced resilience to abiotic stresses. Sustainable rice production systems must therefore focus on optimizing nutrient management, improving seed quality, and adopting eco-friendly practices to ensure long-term productivity and environmental health (5).

Seed presoaking, nutrient management, and foliar supplementation have emerged as pivotal strategies to enhance rice growth and yield sustainably. These techniques not only improve physiological and biochemical processes in plants but also reduce dependence on chemical fertilizers and pesticides, contributing to environmental conservation (6). Seed presoaking is a proven method to improve germination, seedling vigor, and stress tolerance by preconditioning seeds to overcome environmental constraints. Among various agents, seaweed extract has garnered attention due to its bioactive components, including polysaccharides, phytohormones, vitamins, and micronutrients. The extracts derived from seaweed species such as *Kappaphycus alvarezii* and *Sargassum wightii* act as natural bio stimulants, promoting enzymatic activities, improving water and nutrient uptake, and enhancing overall plant growth (7).

Globally, the use of seaweed extracts as biostimulants is gaining considerable traction due to their eco-friendly nature and multifaceted benefits. Seaweed extracts are now widely recognized as sustainable alternatives to chemical fertilizers and growth regulators. Current research highlights their potential to enhance plant growth, yield, and stress resilience across diverse crop species. These extracts contain essential bioactive compounds, such as polysaccharides, phenolic compounds, and plant growth regulators like auxins, cytokinins, and betaines. Studies have shown their efficacy in improving germination rates, root development, photosynthetic activity, and resistance to abiotic stresses like salinity, drought, and extreme temperatures. Countries such as India, China, and European nations are at the forefront of research on seaweed bio-stimulants, with ongoing studies aimed at optimizing their use in large-scale agriculture and reducing reliance on synthetic inputs (7).

Seaweed extracts have demonstrated their ability to mitigate the adverse effects of abiotic stresses such as salinity, drought, and temperature extremes. Presoaking rice seeds in seaweed extract not only enhances early-stage growth but also sets the stage for improved performance during later phenological stages. The integration of this technique with modern agronomic practices can provide a competitive edge in achieving sustainable rice production (8)

Recommended Dose of Fertilizers (RDF) is a standardized nutrient application strategy designed to meet the specific requirements of crops at different growth stages. The balanced provision of macronutrients (nitrogen, phosphorus, and potassium) and micronutrients is essential for maintaining optimal plant health and achieving higher yields. The adoption of RDF in rice cultivation ensures that nutrient deficiencies are minimized, leading to improved physiological and biochemical functioning of the plant (6,8). The effectiveness of RDF can be further amplified when combined with advanced seed treatments and foliar applications. By integrating RDF with other eco-friendly practices, farmers can achieve a sustainable balance between productivity and resource conservation, reducing nutrient runoff and environmental pollution (9).

Foliar spraying is a direct and efficient method of delivering nutrients and bioactive compounds to plants during critical growth stages. In rice cultivation, panicle initiation and flowering are pivotal phases that determine spikelet fertility, seed filling, and yield quality. Nutritional and hormonal deficiencies during these stages can lead to significant yield losses. Seaweed extract-based foliar sprays offer a targeted solution by providing essential nutrients and promoting stress resilience (10).

Sargassum myricocystum (brown algal) and *kappaphycus alvarezii* (red algal) species known for its rich content of bioactive compounds. The extract contains flavonoids, alkaloids, terpenoids, phyto sterols, lectins, vitamins, macromolecules, micronutrients phlorotannins, phenolic compounds, bioactive molecules, antioxidant properties and antimicrobial properties to enhance photosynthetic efficiency, improve enzyme activities, and regulate hormonal balance. Foliar applications at panicle initiation and flowering ensure that the plants receive an additional boost to meet their heightened metabolic demands during these critical periods. This practice has been shown to enhance spikelet fertility, improve seed quality, and maximize yield potential (11, 12).

Pigmented rice varieties like Kavuni have gained prominence due to their dual role as a staple food and a functional food. The anthocyanins present in these varieties confer health benefits such as antioxidant protection, reduced risk of chronic diseases, and improved immune function. However, the agronomic challenges associated with these varieties, including lower yields and longer growth durations, have limited their widespread adoption (13,14). The development of improved pigmented rice strains like Kavuni CO 57 offers a promising solution by combining the health benefits of traditional varieties with the yield potential and stress resilience of modern cultivars. The integration of advanced agronomic practices, such as seed presoaking with seaweed extracts and precise nutrient management, can further enhance the performance of these varieties, making them a viable option for sustainable farming (15).

Despite the proven benefits of seaweed extracts and foliar applications, their combined application in rice cultivation remains underexplored. This study investigates the synergistic effects of seed presoaking with seaweed extract, RDF application, and foliar sprays at panicle initiation and flowering on the physiological, biochemical, and yield parameters of improved kavuni (CO 57). The specific objectives of this study are to evaluate the effects of seed presoaking with seaweed extracts on germination and seedling vigor, to assess the influence of organic manure application on growth parameters, and to determine the impact of foliar sprays on yield attributes. The study hypothesizes that the combined use of these techniques will synergistically enhance the growth and yield of improved kavuni (CO 57), thereby providing a comprehensive strategy for sustainable rice production.

Materials and Methods

The field experiment was conducted at the Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University (TNAU), Madurai, during the Samba season (June–September 2023). The experimental field is located at 09°58'14.62" N latitude, 78°12'15.31" E longitude, and 101 m above mean sea level (MSL). The experimental design comprised two seed treatments and four foliar treatments, arranged in a factorial randomized block design (FRBD) with three replications.

Experimental Design

Seed Presoaking

- T_0: Control (No seed presoaking)
- T_1: 0.5% *Sargassum myricocystum* methanol extract
- T_2: 0.5% *Kappaphycus alvarezii* methanol extract

Foliar Spray Treatments

- F_0: Control (Water only)
- F_1: Panchagavya 3%
- F_2: Seaweed extract 2.5%
- F_3: Fish Amino Acid 1%
- F_4: Vermiwash 10%

This Factorial Randomized Block Design (FRBD) involves 15 treatmental combinations(3 seed treatments × 5 foliar sprays) with three replications for each combination.

The paddy variety CO 57 (Improved kavuni) was used in this experiment. Organic manures were applied basally according to the treatment schedule before transplanting the rice seedlings. The recommended dose of organic manures, as prescribed by the Department of Sustainable Organic Agriculture, was followed. The treatments included green manure applied at 6.25 t/ha, basal application of enriched farmyard manure (EFYM) at 750 kg/ha, and top dressing with vermicompost at 1 t/ha, split into two equal applications at 25 and 45 days after transplanting (DAT).

Assessment of Growth Parameters

Plant height was measured by recording the distance from base of the plant to the tip of the longest leaf. Plant samples were carefully uprooted from the field, dried in an oven at 70°C for 48 hours, and weighed to determine their dry weight. The Leaf Area Index (LAI) was calculated based on the leaf area per plant using the following formula:

$$\text{LAI} = \text{Leaf area per plant} / \text{Ground area occupied} \quad \text{.........(Eqn. 1)}$$

Assessment of Yield Parameters

The number of productive tillers (m^{-2}) was recorded for each plot. At harvest, yield parameters and total yield were calculated. Seeds were individually separated from randomly selected plants in each plot, then dried, cleaned, and weighed using an electronic balance. The average weight was recorded in grams.

Statistical analysis

The data collected on various parameters were analyzed using R software (version 4.2.0, RStudio 2022.02.3+492) to identify significant differences at the 5 % level in a Factorial Randomized Block Design. The agricolae package was utilized for ANOVA and post hoc comparisons using Tukey's HSD test to evaluate variations among the means of 15 treatments. Correlation analysis was conducted to assess relationships between variables, and Principal Component Analysis (PCA) was performed using the FactoMineR and factoextra packages to identify key contributing variables and visualize treatment clustering. Data visualization with ggplot2, including bar plots, boxplots, correlation heatmaps, and PCA biplots, effectively illustrated treatment effects, interactions, and underlying patterns, supporting a comprehensive interpretation of the results.

Results and Discussion

Growth parameters

The highest plant height (121 cm), Leaf area index (LAI) (4.85) and dry matter production (DMP) (5180 kg ha^{-1}) recorded with the presoaking through 0.5 % *Sargassum myricocystum* methanol extract with foliar spray of 2.5 % seaweed extract at PI and Flowering stage (T_1F_2) which was on par with 0.5 % *Kappaphycus alvarezii* methanol extract + 2.5 % seaweed extract (T_2F_2). The lower plant height, LAI and DMP were recorded under control (T_0F_0) and mentioned in Table 1,2 & 3.

The significant variations in plant height, leaf area index (LAI), and dry matter production (DMP) observed in

Table 1. Effect of seaweed extract presoaking and foliar application on plant height (cm) of improved kavuni (CO 57)

Treatments	F_0	F_1	F_2	F_3	F_4	Mean
T_0	91	95	98	95	96	95
T_1	104	114	121	108	111	112
T_2	98	114	118	107	110	109
Mean	98	108	112	103	106	105
SEd	6.767					
CD (P=0.05)	13.668					

Table 2. Effect of seaweed extract presoaking and foliar application on LAI of improved kavuni (CO 57)

Treatments	F_0	F_1	F_2	F_3	F_4	Mean
T_0	3.36	3.76	3.81	3.48	3.54	3.59
T_1	4.04	4.65	4.85	4.21	4.48	4.45
T_2	3.93	4.62	4.80	4.12	4.36	4.37
Mean	3.78	4.34	4.49	3.94	4.13	4.13
SEd	0.400					
CD (P=0.05)	0.807					

Table 3. Effect of seaweed extract presoaking and foliar application on DMP (kg ha^{-1}) of improved kavuni (CO 57)

Treatments	F_0	F_1	F_2	F_3	F_4	Mean
T_0	3946	4224	4312	4037	4115	4127
T_1	4532	5028	5180	4726	4836	4860
T_2	4379	4931	5142	4651	4805	4782
Mean	4286	4728	4878	4471	4585	4590
SEd	333.239					
CD (P=0.05)	672.990					

this study highlight the potential of Seaweed extracts as potent bio-stimulants in agricultural systems. The remarkable performance of *Sargassum myricocystum* and *Kappaphycus alvarezii* methanol extracts, particularly when applied as presoaking and foliar sprays, demonstrates the intricate mechanisms by which seaweed extracts can enhance plant growth and physiological processes.

Seaweed extracts (SE) are rich in a wide range of bioactive compounds, including phytohormones, sterols like fucosterol, carbohydrates, polysaccharides, sugars, polyphenols such as flavonoids, macro- and micronutrients, vitamins, lipids, amino acids, and proteins, including enzymatic components (16,17). Among the bioactive polysaccharides identified in SE are galactans (e.g., carrageenans and agarans), floridean starch, ulvans, laminarin, fucoidan, and alginic acid, along with lignin and cellulose, which contribute significantly to plant health and development (17).

These compounds may act as signalling agents, influencing critical biochemical pathways at both transcriptional and post-translational levels, including the regulation of microRNAs. This interaction results in the differential expression of key genes that are crucial for plant growth and development. Seaweed extract application has been found to activate genes involved in cellular metabolism, including those responsible for lipid, amino acid, and nucleotide synthesis, glycolysis, and molecular transport. Additionally, genes associated with cell structure and cell wall development are also upregulated, enhancing overall plant physiological processes (18).

Furthermore, SE has been shown to upregulate genes linked to stress responses. For example, genes involved in abscisic acid (ABA) signalling, Na^+/K^+ ion transporters, late embryogenesis abundant (LEA) proteins, dehydrins, and aquaporins are enhanced in plants experiencing abiotic stress treated with SE. This regulatory effect boosts the plant's ability to cope with adverse environmental conditions. (19 - 23).

Ascophyllum nodosum extract increased the expression of genes related to salinity tolerance in *Amaranthus tricolor*. Plants treated with seaweed extracts upregulated the genes involved in cell wall synthesis and stress responses (19).

The maximum plant height of 121 cm achieved with *Sargassum myricocystum* methanol extract is particularly noteworthy. Recent studies by Kumar et al. (24) have increasingly recognized seaweed extracts as promising growth regulators that stimulate cell elongation and division. The bioactive compounds in marine macroalgae, such as auxins, cytokinins, and gibberellins, play crucial roles in promoting vertical growth and overall plant architecture.

The application of seaweed extract has been shown to significantly enhance plant height across various crops. In soybean, applying seaweed extract at a rate of 500 ml ha^{-1} during the flowering stage led to a notable increase in plant height, as reported by Guerreiro et al. (25). Similarly, in rice, the soil application of seaweed extract gel at 12.5 kg ha^{-1}, combined with a foliar spray of 0.5 % seaweed extract at tillering and panicle initiation stages, resulted in a significant improvement in plant height, as demonstrated by Deepana et al. (26). Moreover, the combined application of vermicompost, rhizobium, phosphorus-solubilizing bacteria (PSB), and seaweed extract significantly increased plant height compared to treatments without seaweed extract in French bean, according to Rai et al. (27). These findings highlight the multifaceted role of seaweed extracts in promoting robust vegetative growth across diverse agricultural systems.

The observed leaf area index of 4.85 demonstrates the profound impact of seaweed extracts on canopy development. Enhanced LAI is crucial for photosynthetic efficiency, light interception, and overall biomass accumulation. Research by Kumar et al. (28) suggests that bioactive compounds in seaweed extracts can stimulate leaf expansion by modulating cell wall plasticity and promoting cell division in leaf tissues.

The impressive dry matter production of 5180 kg ha^{-1} underscores the comprehensive growth-promoting effects of seaweed extracts. Enhanced DMP reflects improved photosynthetic efficiency, nutrient assimilation, and overall plant metabolism. A meta-analysis by Johnson et al. (29) on agricultural bio-stimulants highlighted the multi-faceted mechanisms through which Seaweed extracts contribute to biomass accumulation. Studies on pigmented rice varieties have also highlighted the benefits of bioactive compounds. Pigmented rice, rich in anthocyanins and other antioxidants, has been shown to improve stress tolerance and nutritional quality (13).

The use of seaweed-based bio stimulants has demonstrated significant benefits in improving dry matter production across various crops. For instance, Pramanick et al. (30) reported that applying 15 % *Kappaphycus* sap combined with the recommended dose of fertilizer (RDF) significantly increased dry matter production in greengram. Similarly, Godlewska and Ciepiela (31) observed that the bio stimulant Algex, derived from *Ascophyllum nodosum*, effectively enhanced dry matter production in red clover when compared to untreated control plots In rice, Deepana et al. (26) highlighted that a combination of soil-applied seaweed extract gel at 12.5 kg ha^{-1} and foliar sprays of 0.5 % seaweed extract at critical growth stages, such as tillering and panicle initiation, resulted in a substantial increase in dry matter production. These findings underscore the potential of seaweed extracts in optimizing biomass accumulation across different crop types.

Yield parameters

Yield attributes were significantly influenced by different foliar applications (Table 4,5,6). Application of 0.5 % *Sargassum myricocystum* methanol extract with foliar spray of 2.5 % seaweed extract at PI and Flowering stage (T_1F_2) registered a higher number of productive tillers m^{-2} (281), number of filled seeds panicle^{-1} (170) and 1000 seed weight (22.34 g). However, treatment T_1F_2 was on par with 0.5 % *Kappaphycus alvarezii* methanol extract + 2.5 % seaweed extract(T_2F_2). Control (T_0F_0) registered lower yield parameters.

The highest number of productive tillers (281) recorded under the treatment T_1F_2 (0.5 % *Sargassum myricocystum* methanol extract + 2.5 % seaweed foliar spray) indicates its efficacy in improving tillering capacity. This result can be attributed to the rich composition of seaweed extracts, including cytokinins, which are known to stimulate cell division and tiller formation. Foliar applications during the panicle initiation (PI) and flowering stages ensure the timely availability of nutrients and growth-promoting substances, which are critical for tiller productivity.

Table 4. Effect of seaweed extract presoaking and foliar application on no. of productive tillers m^{-2} of improved kavuni (CO 57)

Treatments	F_0	F_1	F_2	F_3	F_4	Mean
T_0	203	217	221	209	211	212
T_1	230	265	281	238	248	252
T_2	226	256	276	234	242	247
Mean	220	246	259	227	234	237
SEd			20.232			
CD (P=0.05)			40.859			

Table 5. Effect of seaweed extract presoaking and foliar application on no. of filled grains panicle^{-1} of improved kavuni (CO 57)

Treatments	F_0	F_1	F_2	F_3	F_4	Mean
T_0	104	117	121	110	112	113
T_1	128	159	170	137	148	148
T_2	126	156	165	132	144	145
Mean	119	144	152	126	135	135
SEd			17.103			
CD (P=0.05)			34.541			

Table 6. Effect of seaweed extract presoaking and foliar application on 1000 seed weight (g) of improved kavuni (CO 57)

Treatments	F_0	F_1	F_2	F_3	F_4	Mean
T_0	20.88	21.15	21.37	21.10	21.07	21.11
T_1	21.52	22.23	22.34	21.87	22.06	22.00
T_2	21.41	22.11	22.31	21.71	21.95	21.90
Mean	21.27	21.83	22.01	21.56	21.69	21.67
SEd			0.488			
CD (P=0.05)			0.986			

Summary Table (1-6)

Treatment	Plant height (cm)	LAI	DMP (kg ha^{-1})	No. of productive tillers m^{-2}	No. of filled grains panicle^{-1}	1000 seed weight (g)
T_1F_2	121	4.85	5180	281	170	22.34
T_2F_2	118	4.80	5142	276	165	22.31
T_0F_0 (Control)	91	3.36	3946	203	104	20.88

Similar results were observed by Sanjay Singh et al. (32), where seaweed extract treatments increased tillering in rice by enhancing nutrient uptake and hormonal balance. Additionally, Nayak et al. (33) highlighted that the application of seaweed extracts improves root growth and nutrient mobilization, supporting more robust tiller development.

The treatment T_1F_2 also recorded a higher number of filled seeds per panicle (170), a key determinant of rice yield. This improvement may be linked to enhanced photosynthetic efficiency and nutrient translocation facilitated by the bioactive compounds in *Sargassum*. Seaweed extracts are rich in macronutrients like nitrogen and potassium, as well as trace elements such as zinc and boron, which play a vital role in seed filling.

Studies by Pramanick et al. (30) and Ayodeii et al. (34) have shown that seaweed extracts boost grain-filling efficiency by improving source-sink dynamics and mitigating abiotic stress during critical reproductive stages.

The 1000-seed weight (22.34 g) under T_1F_2 reflects the positive influence of seaweed extracts on seed quality. Improved seed weight is likely due to better nutrient assimilation and hormone regulation, which enhance starch deposition in developing seeds. Treatments with *Kappaphycus alvarezii* (T_1F_2) yielded comparable results, indicating that different seaweed species exhibit similar growth-promoting effects when applied at appropriate concentrations and stages.

The application of seaweed extracts has been shown to enhance key yield parameters across a variety of crops. In chickpea, treating plants with 1 ml/L of seaweed extract significantly increased the number of seeds per pod, as reported by Boghdady et al. (35). Similarly, in garden pea, a combination of 10 % *Kappaphycus* sap and the recommended dose of fertilizer (RDF) led to a notable improvement in the number of seeds per pod compared to the control, as observed by Garai et al. (36).

Research by Yogendra et al. (37) emphasized that seaweed-based foliar sprays at flowering stages enhance seed weight by increasing carbohydrate synthesis and transport. Furthermore, the presence of phenolic compounds in seaweed extracts aids in stress tolerance, contributing to better seed quality under suboptimal conditions (38).

In terms of seed weight, Rathore et al. (39) demonstrated that applying a 15 % seaweed extract significantly enhanced the test weight in soybean. Additionally, in hybrid maize, a combined treatment of 15 % *Gracilaria* sap and 10 % *Gracilaria* sap resulted in a significant increase in the weight of 100 seeds compared to untreated controls (40). In rice, Deepana et al. (26) highlighted that soil application of seaweed extract gel at 12.5 kg/ha, along with foliar sprays of 0.5 % seaweed extract during tillering and panicle initiation stages, significantly increased the weight of 1000 seeds. These studies collectively underscore the effectiveness of seaweed extracts in enhancing seed and seed attributes across diverse crop systems.

Seed and straw yield

The highest seed yield (4552 kg ha^{-1}) and straw yield (6370 kg ha^{-1}) were recorded with the application of 0.5 % *Sargassum myricocystum* methanol extract with foliar spray of 2.5 % seaweed extract at PI and Flowering stage (T_1F_2). However, T_2F_2 was statistically on par with 0.5 % *Kappaphycus alvarezii* methanol extract + 2.5 % seaweed extract(T_2F_2) (Fig. 1). Control (T_0F_0) registered a significantly lower yield for treatment without the application of foliar.

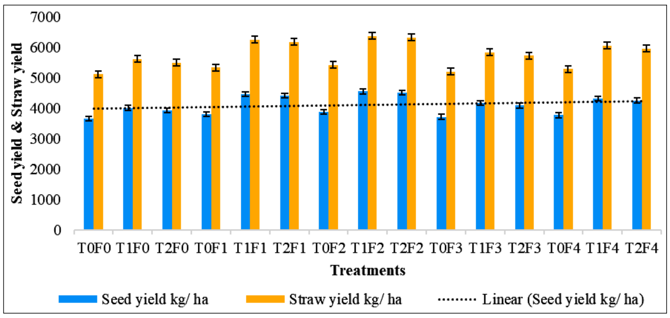

Fig. 1. Effect of seaweed extract presoaking and foliar application on yield of improved kavuni (CO 57).

Seaweed extracts are known to enhance seed yield by supplying essential nutrients, growth hormones, and other bioactive compounds. These extracts contain cytokinins, auxins, and gibberellins, which stimulate root and shoot growth, promote flowering, and improve seed filling. Enhanced root systems lead to better nutrient uptake, especially nitrogen and potassium, which are critical for reproductive growth (41).

Foliar application of bio-stimulants and seaweed extracts has shown substantial improvements in seed yield across various crops. In black gram, applying bio-stimulants such as Bio-zyme Crop+ and Quantis significantly enhanced seed yield compared to untreated controls (42). Similarly, spraying seaweed extract at a concentration of 7.5 % resulted in a notable increase in the seed yield of wheat, as reported by Kumar et al. (43).

In onion, the application of seaweed extract at concentrations of 0.5 %, 1 %, 2 %, and 3 % significantly boosted seed yield, demonstrating the versatility of seaweed extracts in improving productivity (44). For green gram, Pramanick et al. (30) found that the use of 15 % *Kappaphycus* sap combined with the recommended dose of fertilizer (RDF) increased seed yield by 38.97 % compared to the control treatment.

Additionally, in wheat, Sarita et al. (45) observed that applying seaweed extract at 4 ml per litter of water during the tillering and heading stages significantly improved the harvest index. These findings collectively underscore the effectiveness of seaweed-based biostimulants in enhancing seed yield and related parameters across different cropping systems.

Incorporating seaweed extracts into agricultural practices offers a promising path towards sustainable farming. The multifaceted benefits range from improved soil health and reduced chemical dependency to enhanced resilience and biodiversity. By adopting these natural bio stimulants, farmers can contribute to a more sustainable and environmentally friendly agricultural system, ensuring food security and ecological balance for future generations.

Correlation analysis

Correlation analysis conducted to evaluate the relationship between growth parameters and yield (Fig. 2) revealed that plant height (1.0), LAI (0.98), and DMP (0.99) of the improved kavuni (CO 57) paddy were strongly and positively associated with seed yield. This finding emphasizes that plant height, LAI, and DMP are critical determinants

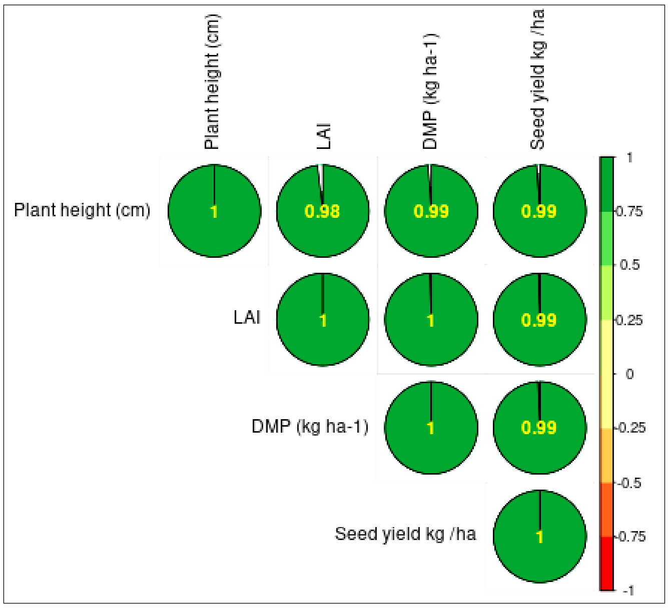

Fig. 2. Correlation analysis of growth parameters and yield of improved kavuni (CO 57).

for achieving higher yields. Similar observations were reported by Russinga et al. (46) and Saketh et al. (47), who demonstrated that growth parameters significantly contribute to and are positively correlated with seed yield in various crops.

Principal Component Analysis

Principal component analysis (PCA) was used to examine the relationships among the measured growth and yield parameters (Fig. 3). This statistical method is particularly useful for simplifying datasets with many correlated variables by reducing them to a smaller number of principal components. In this analysis, the first principal component (PC1) accounts for99.0 % of the total variance, while the second principal component (PC2) captures 0.5 %. Together, PC1 and PC2 explain 99.5 % of the variance in the data.

- No. of Productive Tillers/plant, Seed yield ha^{-1}, and DMP have strong contributions to PC1 or PC2, as their arrows are long.
- No. of Filled seeds/panicle and 1000 Seed Weight (g) are also strongly related and grouped in the same direction.
- T_1F_2 and T_2F_2 are located near variables like Seed yield ha^{-1}, indicating that these treatments had high seed yield and other positively correlated traits.
- Treatments like T_3F_4 are further away, indicating weaker performance or a different trait profile.
- Strong relationships exist between productive traits like Seed yield ha^{-1}, DMP, and 1000 Seed Weight, as their arrows are closely aligned.
- Treatments clustered near these variables are likely better-performing in yield and related attributes.
- This biplot effectively visualizes the relationships between treatments and agronomic traits. High-performing treatments (T_1F_2, T_2F_2) are associated with traits such as seed yield, productive tillers, and biomass.

Recent studies have highlighted the effectiveness of PCA in agricultural research. For instance, Vikas Singh and Alka Singh (48) applied PCA to Indian agricultural crop data and found that only two principal components explained 93% of the total variability. Similarly, Mubashir Jamil and Vijay Lakshmi (49) used PCA for crop acreage estimation in Dhampur, India, demonstrating its utility in managing agricultural resources.

Conclusion

The present findings demonstrated that presoaking seeds in 0.5 % methanol extract of *Sargassum myricocystum*, combined with a 2.5 % seaweed extract foliar spray at panicle initiation and flowering (T_1F_2), significantly improved the growth, yield parameters, and overall yield of improved kavuni (CO 57) during the Samba season (2023). The findings highlight the potential of *Sargassum* extracts to boost rice productivity. Future research should focus on optimizing application rates and integrating other organic inputs for wider agricultural adoption.

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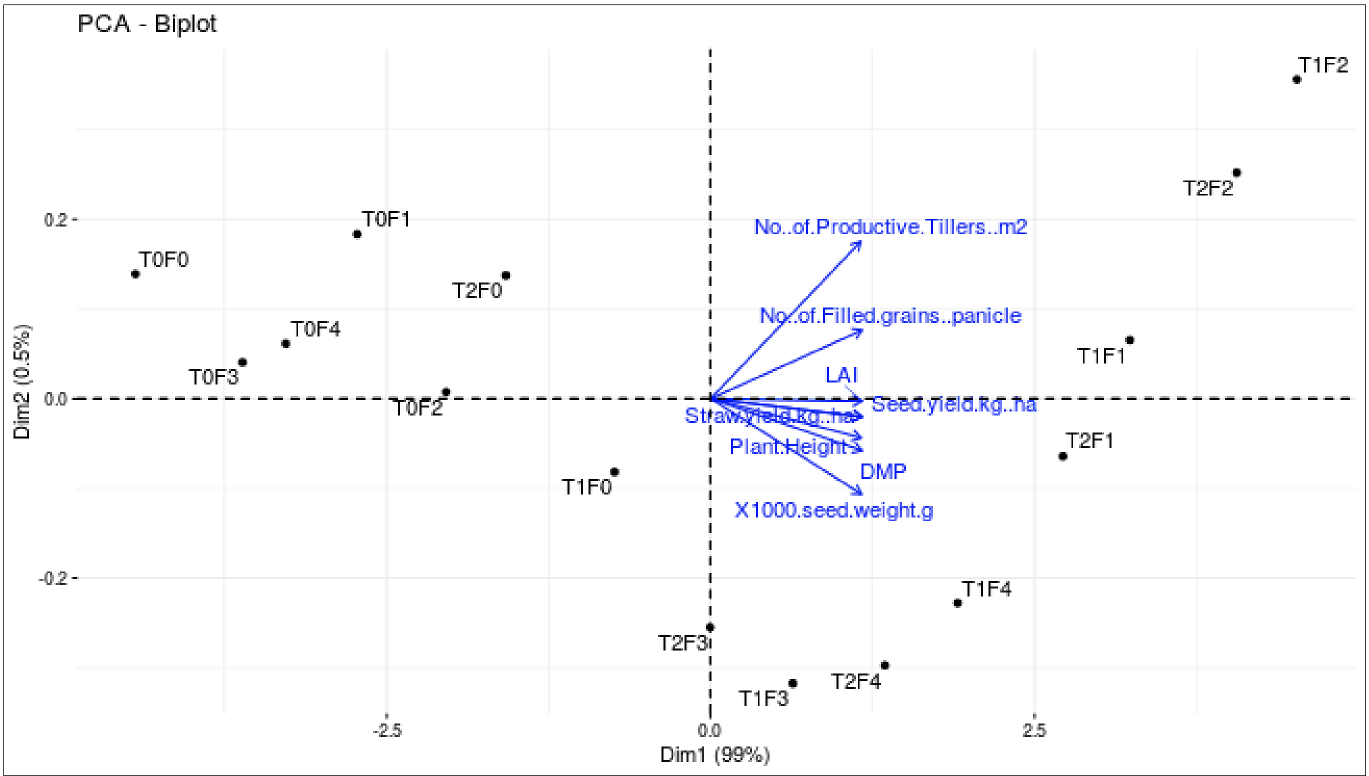

Fig. 3. The principal component analysis shows treatments impact on variables such as growth and yield parameters of improved kavuni (CO 57).

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Authors' contributions

RE carried out the experiments and prepared the original draft of the writing. KS Conceptualization. AA and TS supervised the work and drafted and reviewed the manuscript. MLM participated in the sequence alignment and editing. AG visualization. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

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

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