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Effect of foliar application of Ascophyllum nodosum-based biostimulant on early growth and physiology of pearl millet under semi-arid conditions

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ABSTRACT

Pearl millet (*Pennisetum glaucum*) is an important cereal crop cultivated in arid and semi-arid regions, but its early growth is often hampered by inadequate rainfall and low soil fertility. This study investigated the impact of a seaweed-based biostimulant derived from Ascophyllum nodosum on the early growth and physiological characteristics of pearl millet in a dry area of Maharashtra, India. A field trial was conducted using a randomized complete block design with three treatments: T0 (control), T1 (2% foliar biostimulant), and T2 (4% foliar biostimulant). The biostimulant was sprayed at 15 and 30 days after sowing. By 45 days, the 4% treatment exhibited the best results, with significant enhancements in plant height, root length, biomass, and chlorophyll content (SPAD values). Although the increase in seedling emergence was not statistically significant, it indicated better uniformity and vigor. These findings suggest that seaweed-based biostimulants can serve as a beneficial and eco-friendly alternative to enhance early growth in pearl millet, particularly in rainfed areas. This method promotes low-cost, sustainable farming for small-scale farmers. Furthermore, it creates new opportunities for integrating natural growth enhancers into traditional practices, thereby reducing reliance on chemical inputs while enhancing early-stage crop performance under challenging field conditions.

KEYWORDS

Seaweed biostimulant; Pearl millet; Early growth parameters; Sustainable agriculture; Dryland farming

ARTICLE HISTORY

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Introduction

Pearl millet (*Pennisetum glaucum*) is a vital staple crop in many parts of Asia and Africa, particularly within arid and semi-arid regions. Its ability to thrive under high temperatures, limited rainfall, and marginal soils makes it indispensable to farming systems where other cereals falter [1]. In India, pearl millet is primarily cultivated during the kharif season and plays a dual role serving as both a nutritious food source and a valuable feed crop for livestock. For millions of smallholder farmers, especially those reliant on rainfed agriculture, it is a crop that supports livelihoods, nutrition, and ecological resilience [2]. Despite its hardy nature, pearl millet is vulnerable during its early growth stages. Inconsistent monsoon patterns and inherently low soil fertility in dryland zones often lead to poor seed germination, weak seedling establishment, and uneven plant stands. These early-stage challenges directly influence biomass accumulation, nutrient uptake, and ultimately, yield. Therefore, improving early vigor is essential to achieving higher productivity and crop stability in dryland conditions [3].

Recent global shifts in agricultural practices reflect a growing interest in sustainable, low-input farming solutions. One promising innovation in this regard is the use of biostimulants, natural or biologically derived substances that enhance plant growth and development [4]. Among them, seaweed-based biostimulants have gained prominence due to their environmentally friendly nature and broad efficacy. Extracted primarily from brown algae such as Ascophyllum nodosum, these formulations contain a mixture of plant growth regulators (auxins, cytokinins, gibberellins), amino acids, polysaccharides, and micronutrients. These compounds work synergistically to enhance physiological processes like root initiation, chlorophyll synthesis, water uptake, and stress tolerance [5].

In regions like Solapur in Maharashtra, where erratic rainfall and limited access to synthetic inputs hinder agricultural productivity, seaweed biostimulants represent a practical and affordable option. Their foliar application is simple, non-toxic, and compatible with existing cropping practices [6]. However, despite their documented benefits in horticultural and high-value cereal crops, there is limited field-based evidence supporting their use in millets, particularly under actual semi-arid farming conditions [7].

This study was designed to address that research gap. By examining the influence of Ascophyllum nodosum-based biostimulants on early vegetative growth and physiological parameters of pearl millet, it aims to provide field-level insights that are both scientifically relevant and practically useful. The research focuses on the early stages of crop development, as interventions during this period have a significant bearing on overall plant performance and eventual yield [8].

Understanding how such natural inputs perform under open-field, rainfed conditions is crucial for scaling them in similar agro-climatic zones. This study not only evaluates the biological response of the crop but also reflects on the potential

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of integrating sustainable growth enhancers into dryland agriculture. In doing so, it contributes to the broader movement toward climate-resilient and resource-efficient farming systems that prioritize ecological balance alongside productivity [9].

Literature Review

The increasing demand for sustainable agricultural practices has brought biostimulants into focus as eco-friendly inputs capable of enhancing crop productivity and resilience. Among the various types of biostimulants, those derived from seaweeds have gained widespread attention for their broad-spectrum benefits [10]. Seaweed-based biostimulants, especially those extracted from brown algae like Ascophyllum nodosum, are rich in biologically active compounds such as auxins, cytokinins, gibberellins, amino acids, vitamins, and trace minerals. These compounds play critical roles in modulating plant physiological responses, particularly under stress conditions [11].

Several studies have demonstrated the positive impact of seaweed extracts on seed germination and seedling establishment. These early stages of plant growth are often the most vulnerable, especially in low-input and stress-prone environments [12]. Seaweed extracts have been shown to stimulate enzymatic activity, enhance root development, and improve nutrient uptake, leading to more vigorous seedlings [13]. In crops like tomato, sweet pepper, and maize, foliar applications of seaweed extracts have resulted in increased chlorophyll content, improved photosynthetic efficiency, and stronger root systems, all of which contribute to better plant growth and yield potential [14].

One of the most critical advantages of seaweed-based biostimulants is their ability to enhance plant resilience to abiotic stress. Environmental stresses such as drought, heat, and salinity often result in oxidative stress within plant tissues, damaging cellular structures and impairing metabolic functions [15]. Seaweed extracts help mitigate these effects by activating antioxidant defense mechanisms in plants. These include the upregulation of enzymes such as superoxide dismutase, catalase, and peroxidase, which neutralize reactive oxygen species (ROS) [16]. In addition, compounds in seaweed extracts improve osmotic balance and regulate stomatal conductance, helping plants maintain hydration and metabolic activity under adverse conditions [17].

In cereal crops, the application of seaweed biostimulants has shown encouraging results. Research in wheat, rice, and maize indicates improvements in growth parameters such as plant height, root biomass, and grain yield following treatment with seaweed extracts [18]. These outcomes are attributed to enhanced nutrient absorption, increased chlorophyll synthesis, and better hormonal regulation. However, while these studies provide a solid foundation, there remains a significant gap in our understanding of how these biostimulants affect underutilized cereals such as millets, which are often grown in marginal environments with limited inputs [19].

Pearl millet, in particular, stands out as a crop that could benefit from seaweed-based interventions. Known for its hardiness and suitability for dryland agriculture, pearl millet is typically cultivated in regions where soil fertility is low and water availability is unreliable [20]. Despite its importance, the crop has not received sufficient research attention compared to other cereals. Studies on finger millet and sorghum have shown that seaweed applications can improve physiological traits, suggesting that similar outcomes might be possible in pearl millet as well [21].

Furthermore, most existing research on seaweed biostimulants has been conducted in controlled conditions such as greenhouses or laboratories. These environments do not accurately represent the challenges faced by farmers operating in open-field, semi-arid conditions [22]. Therefore, there is a pressing need for field-based studies that evaluate the real-world effectiveness of seaweed-based biostimulants in promoting early growth and physiological performance in pearl millet [23].

This literature review highlights the proven benefits of seaweed biostimulants across a range of crops and growing conditions while drawing attention to the underexplored potential in millets. It underscores the importance of field research that accounts for local soil, climate, and management conditions. By addressing this gap, the present study contributes to a growing body of work aimed at enhancing crop performance through sustainable, low-cost inputs suitable for dryland farming systems.

Methodology

Study area

The field experiment was conducted during the 2024 kharif season in the Mohol block of Solapur district, located in Maharashtra, India. This region is part of the semi-arid agro-climatic zone of the Deccan Plateau and is characterized by erratic monsoon rainfall, high evapotranspiration rates, and generally poor soil fertility. The average annual precipitation is approximately 550–600 mm, predominantly received during the monsoon months of June to September. Mean daily temperatures during the cropping period ranged from 24°C to 37°C. The experimental field was situated on sandy loam soil with moderate levels of organic matter but limited in available nitrogen and phosphorus. A comprehensive soil analysis was conducted before sowing, which indicated a neutral pH of 7.6, an electrical conductivity (EC) of 0.38 dS/m, and available nutrients measured at 160 kg/ha of nitrogen, 12 kg/ha of phosphorus, and 185 kg/ha of potassium. This assessment was essential for determining appropriate fertilizer applications and understanding baseline soil fertility.

Experimental design

The study employed a randomized complete block design (RCBD) to minimize experimental error and increase the precision of treatment comparisons. Three treatments were tested:

- T0 – Control (no biostimulant),
- T1 – Foliar application of 2% seaweed-based biostimulant, and
- T2 – Foliar application of 4% seaweed-based biostimulant.

Each treatment was replicated three times to ensure statistical reliability. Individual plots were demarcated at 3 m ×

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3 m, with a buffer zone of 0.5 m between adjacent plots and 1 m between blocks to avoid treatment interference and ensure accurate observations. Treatment allocation was randomized using the RCBD module in R software to eliminate bias and achieve random distribution across the field.

Crop establishment

The test crop was pearl millet (*Pennisetum glaucum*), specifically the high-iron variety 'Phule Dhanshakti', sourced from Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri. Sowing was done manually in the second week of July after sufficient pre-monsoon rainfall. Seeds were sown at a row spacing of 45 cm and plant spacing of 15 cm, using a seed rate of 4 kg/ha to ensure optimal population. Seeds were treated with Trichoderma viride at 10 g/kg to prevent fungal infections and promote healthy germination. Germination was observed daily from day 3 to 10 after sowing to calculate emergence percentage.

Biostimulant application

The biostimulant used was a commercial formulation from brown seaweed Ascophyllum nodosum, known to contain bioactive compounds, including plant growth regulators like auxins, cytokinins, and gibberellins, along with essential amino acids and micronutrients such as iron and magnesium. Foliar applications were done twice at 15 and 30 days after sowing (DAS). A hand-held knapsack sprayer, calibrated to deliver 500 L/ha, ensured uniform application. Spraying was conducted in the early morning to maximize leaf absorption and minimize volatilization. Both leaf surfaces were carefully covered without causing runoff.

Agronomic practices

Uniform agronomic practices were followed across all treatments to ensure comparability. A basal fertilizer dose of 60:40:40 kg/ha N:P:K was applied using urea, single superphosphate (SSP), and muriate of potash (MOP). Fertilizers were incorporated into the soil before sowing. Manual weeding was done at 20 and 40 DAS to control weeds. Soil moisture was monitored weekly using a digital probe. Supplemental furrow irrigation was applied when moisture dropped below 60% of field capacity, simulating near-rainfed conditions. No chemical pesticides or herbicides were used to maintain natural and sustainable practices.

Data collection

Observations were recorded at 45 DAS to capture early-stage growth and physiological parameters. The following metrics were measured:

- **Seedling Emergence (%):** Monitored from day 3 to 10 after sowing. Emergence percentage was calculated as the ratio of emerged seedlings to total seeds sown per plot.
- **Plant Height (cm):** Measured from the base to the tip of the tallest leaf using a meter scale for ten randomly selected plants per plot.
- **Root Length (cm):** Determined by carefully uprooting plants, washing roots to remove soil, and measuring the longest root.
- **Fresh and Dry Biomass (g/plant):** Fresh biomass was recorded immediately after harvest. Samples were then dried in a hot air oven at 65°C for 72 hours until constant weight to determine dry biomass.
- **Chlorophyll Content (SPAD units):** Chlorophyll content was assessed using a SPAD-502 Plus chlorophyll meter. Three readings per leaf were taken from the mid-portion of the leaf, and average values were computed.

Ethical and environmental considerations

The experimental design adhered to ethical and environmental best practices. No synthetic pesticides or herbicides were used, minimizing ecological impact. Biostimulants and fertilizers were applied following recommended safety guidelines to avoid leaching or runoff. Indigenous practices were integrated through consultations with local farmers and extension officers. Waste generated during fieldwork, such as seed packets and empty biostimulant containers, was disposed of according to institutional and environmental safety protocols. The study complied with all institutional biosafety standards.

Results

The application of seaweed-based biostimulant had a measurable and generally positive impact on the early vegetative growth and physiological performance of pearl millet at 45 days after sowing (DAS). The results revealed a consistent improvement across all assessed parameters seedling emergence, plant height, root length, biomass (fresh and dry), and chlorophyll content (SPAD value) with increasing concentrations of the biostimulant.

Seedling emergence

Seedling emergence percentage, an early indicator of vigor and establishment, gradually increased across treatments. The control plot (T0) recorded 76.2% emergence. The 2% seaweed extract treatment (T1) increased this to 79.8%, while the 4% treatment (T2) further raised it to 82.5%. Although the increase was not statistically significant ($p > 0.05$), the upward trend suggests a favorable effect of seaweed extract on early seedling vigor, likely due to plant hormones like auxins and cytokinins in the biostimulant that stimulate germination and uniform sprouting.

Plant height

Plant height, a vital agronomic trait reflecting nutrient uptake and physiological processes, responded significantly to biostimulant application. In the control (T0), plants averaged 38.6 cm. T1 plants reached 43.7 cm, and T2 plants 45.0 cm. The 16.4% increase in T2 over T0 was statistically significant ($p < 0.05$). This enhancement suggests improved vegetative growth, likely due to better cell division and elongation triggered by bioactive compounds in the seaweed formulation.

Root length

Root length, an essential parameter for below-ground development and nutrient acquisition, improved markedly. The mean root length in the control (T0) was 13.8 cm. Treatment T1 recorded 16.2 cm, while T2 increased further to 16.8 cm. The 21.8% increase in T2 over T0 was statistically significant ($p < 0.05$), highlighting the biostimulant's role in promoting

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stronger, more extensive root systems. Enhanced root growth is critical in semi-arid environments, where water and nutrients are often limited.

Biomass accumulation

Biomass production is a reliable integrative measure of plant growth performance. Both fresh and dry biomass were significantly influenced by biostimulant treatments. Fresh biomass increased from 18.4 g/plant in T0 to 20.7 g/plant in T1 and 22.5 g/plant in T2. Similarly, dry biomass rose from 5.6 g in T0 to 6.7 g in T1 and 7.4 g in T2. These increases, especially the 32.1% improvement in dry biomass in T2 over T0, were statistically significant, underscoring the biostimulant's efficacy in enhancing carbon assimilation and metabolism. Improved biomass reflects better nutrient use efficiency and stress resilience.

Chlorophyll content (SPAD Value)

Chlorophyll content, measured by a SPAD meter, indicates photosynthetic capacity and nitrogen status. The control (T0) recorded an average SPAD value of 35.1. Treatment T1 increased to 38.9, while T2 reached 41.2. The 17.4% increase in T2 relative to T0 suggests enhanced chlorophyll biosynthesis, likely due to micronutrients and amino acids in the seaweed extract. Higher SPAD readings are often linked to better photosynthesis and improved energy production for growth.

Visual observations

Qualitative observations during crop growth supported the quantitative data. Plants in the 4% biostimulant treatment (T2) showed visibly deeper green foliage, more upright, turgid leaves, and sturdier stems than control plots. These traits indicate better physiological health and greater resilience to biotic and abiotic stresses. T0 plants appeared slightly pale with thinner stems and less uniform growth, especially under intermittent water stress.

Table and graphical representation

A comprehensive summary of the recorded parameters is provided in Table 1 below:

Table 1. Effect of seaweed biostimulant on growth and physiological parameters of pearl millet at 45 DAS.

Parameter	Control (T0)	2% Biostimulant (T1)	4% Biostimulant (T2)	% Increase (T2 vs T0)
Seedling Emergence (%)	76.2	79.8	82.5	+8.3%
Plant Height (cm)	38.6	43.7	45.0	+16.4%
Root Length (cm)	13.8	16.2	16.8	+21.8%
Fresh Biomass (g/plant)	18.4	20.7	22.5	+22.3%
Dry Biomass (g/plant)	5.6	6.7	7.4	+32.1%
SPAD Value	35.1	38.9	41.2	+17.4%

In addition to the tabulated data, a bar chart was prepared to visually represent the effect of each treatment on the measured parameters. Each grouped set of bars corresponds to one treatment level (T0, T1, T2), with individual bars representing plant height, root length, biomass, and SPAD values. The chart illustrates a clear and consistent trend of increased growth performance with higher biostimulant concentration. The graphical representation shows the effect of different seaweed biostimulant treatments on pearl millet's early growth and physiological parameters. Each bar cluster represents one treatment level (Control, 2%, and 4% biostimulant), with individual bars showing the measured traits like seedling emergence, plant height, root length, biomass, and SPAD values. This clearly illustrates the performance improvement across treatments, especially with the 4% application (Figure 1).

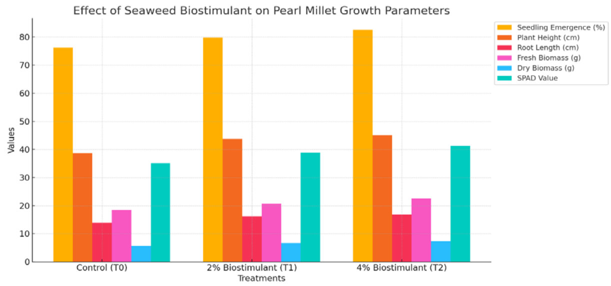

Figure 1. Effect of seaweed biostimulant on pearl millet growth parameters.

Interpretation and implications

The results from this field trial demonstrate that the foliar application of a seaweed-derived biostimulant, particularly at a 4% concentration, significantly improves early-stage vegetative growth and physiological performance in pearl millet. The positive dose-response relationship observed across all key metrics supports the hypothesis that seaweed extracts can serve as effective, eco-friendly growth promoters in rainfed, semi-arid farming systems. Given the constraints of nutrient-poor soils and erratic rainfall in regions like Solapur, such biostimulants offer a promising strategy for enhancing crop resilience and productivity with minimal ecological impact.

Discussion

The findings of this study provide valuable insights into the role of seaweed-based biostimulants in enhancing the early growth and physiological characteristics of pearl millet, especially under semi-arid field conditions. The application of Ascophyllum nodosum-derived biostimulant demonstrated a consistent trend of improvement across all measured parameters, with the 4% treatment (T2) showing the most pronounced effects.

One of the most notable observations was the increase in plant height and root length under the T2 treatment. Enhanced shoot and root growth in the early stages suggest better access to water and nutrients, which is crucial in dryland agriculture where resource availability is inherently limited. The deeper and

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more extensive root systems observed in treated plots likely improved the plant's ability to extract moisture from the soil profile, contributing to greater resilience during dry spells. These improvements align well with existing studies in other cereals where seaweed extracts enhanced vegetative growth and root development.

Biomass accumulation, both fresh and dry, was significantly higher in the biostimulant-treated plants. This suggests an improvement in photosynthetic efficiency and nutrient use, both of which are vital for strong early plant performance. The chlorophyll content, measured using SPAD values, further supports this interpretation. Plants in the T2 treatment exhibited higher SPAD readings, indicating greater chlorophyll density and hence, better light-harvesting capacity. Chlorophyll is closely linked to nitrogen status and overall plant health, making it a reliable indicator of early vigor [24].

Although the increase in seedling emergence was not statistically significant, the trend toward improved emergence and uniformity in treated plots is agronomically meaningful. Early and uniform establishment often determines the success of a crop in marginal conditions. This finding highlights the potential of biostimulants to support seedling vigor, even if statistical significance is not achieved.

From a physiological standpoint, the effectiveness of Ascophyllum nodosum extract can be attributed to its bioactive composition. The presence of phytohormones such as cytokinins and auxins may have played a key role in stimulating cell division, elongation, and root initiation. Additionally, trace elements and amino acids present in the extract likely contributed to enzymatic activity and metabolic regulation, helping plants manage stress more efficiently.

These results are especially relevant for regions like Solapur, where rainfall is unpredictable and soils are often depleted. The use of a natural, foliar-applied product that enhances early-stage growth without requiring changes to sowing or tillage practices represents a significant advantage. Moreover, the simplicity of application makes this intervention accessible to smallholder farmers with limited technical support or mechanization.

When compared with chemical fertilizers or growth regulators, seaweed-based biostimulants offer a cleaner, low-risk alternative with minimal environmental impact. They do not contribute to soil or water contamination and can be used alongside organic farming principles. This aligns well with broader goals of sustainable and climate-resilient agriculture, especially as the frequency of extreme weather events increases. It is important to recognize the study's scope and limitations. The research focused exclusively on early growth metrics at 45 DAS. While these indicators are strongly correlated with final yield, long-term monitoring would provide a more comprehensive understanding of biostimulant efficacy throughout the full crop cycle. Additionally, exploring combinations with organic or mineral fertilizers could further optimize crop performance.

Future studies could expand to evaluate effects across different soil types, climate conditions, and millet varieties. Economic analyses assessing cost-to-benefit ratios and farmer adoption rates would also enhance the practical value of the research. Engaging with local agricultural extension systems to promote field demonstrations could accelerate the scaling of such interventions.

This study confirms that foliar application of Ascophyllum nodosum-based biostimulant, particularly at a 4% concentration, can significantly improve early growth performance in pearl millet under semi-arid conditions. The results underscore the importance of integrating natural inputs into conventional farming systems to enhance productivity while maintaining environmental integrity.

Conclusions

This study highlights the potential of using a seaweed-based biostimulant derived from Ascophyllum nodosum to improve the early growth performance of pearl millet under semi-arid, rainfed conditions. The 4% foliar treatment consistently outperformed the control and 2% treatments in terms of plant height, root development, biomass accumulation, and chlorophyll content, indicating strong physiological benefits. These outcomes suggest that seaweed biostimulants can enhance early vigor and improve crop resilience in the face of climatic and edaphic stressors.

Importantly, the intervention is simple to apply, eco-friendly, and compatible with existing farming practices, making it particularly suitable for resource-limited smallholder farmers. The observed improvements in plant health and early development have practical implications for improving yield stability and reducing reliance on synthetic inputs. These attributes align with global efforts to promote climate-smart and sustainable agricultural solutions.

While the results are promising, future research should investigate long-term effects on yield, stress tolerance, and cost-effectiveness across diverse agro-climatic zones. Integrating seaweed-based biostimulants into holistic nutrient management strategies could further support their adoption. Overall, this study contributes to the growing body of evidence supporting natural plant growth enhancers and highlights their role in promoting resilient, low-input farming systems.

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Disclosure statement

The authors declare that they have no competing interests.

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