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Enhancing Growth and Yield of Foxtail Millet Using Pearl Oyster Biofouling Fertilizer

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Abstract

Hotong (*Setaria italica* L.), or foxtail millet, is an emerging alternative cereal crop with high adaptability to marginal environments and considerable nutritional value. This study aimed to evaluate the effects of liquid organic fertilizer (LOF) derived from pearl oyster (*Pinctada maxima* L.) biofouling waste on the growth and yield of hotong cultivated under tropical conditions in Mamala Village, Maluku. A factorial randomized block design was implemented using four fertilizer concentrations (0, 10, 20, and 30 mL·L^{-1}) and two application timings (25 and 50 days after planting, DAP). Results revealed that LOF application significantly enhanced both vegetative and reproductive traits. The concentration of 30 mL·L^{-1} applied at 25 DAP produced the largest leaf area (64.17 cm^2) and highest total biomass (306.91 g), indicating improved nutrient uptake and photosynthetic capacity during early growth. Yield components—including plant height, panicle number, and grain weight—increased by 40–60% relative to the control treatment. These findings demonstrate that organic fertilizer made from aquaculture biofouling waste functions as an effective nutrient source for cereal crops while contributing to environmentally responsible waste management. The integration of aquaculture residues into agricultural fertilizer production aligns with circular economy principles by promoting nutrient recycling, reducing reliance on synthetic fertilizers, and mitigating marine pollution associated with biofouling disposal. The implications of this research highlight the potential for scalable, low-cost, and eco-friendly fertilization strategies that enhance food security in marginal farming areas, strengthen coastal community resilience, and support sustainable linkages between aquaculture and terrestrial crop production systems

INTRODUCTION

Food security continues to be one of the most pressing global challenges of the 21st century, particularly as the world faces the dual pressures of population growth and environmental degradation. Global cereal demand is projected to rise by 30–40% by 2050, while arable land and freshwater resources are declining (Codreanu et al., 2025). The current reliance on major staples, such as rice, wheat, and maize, is increasingly unsustainable, given their high input requirements, susceptibility to climate variability and ecological impacts associated with chemical fertilizers and pesticides (Foley et al., 2011). Therefore, diversifying food sources through the development of alternative cereals that are nutritionally rich, environmentally resilient, and locally adaptable has become a critical strategy to achieve sustainable food security.

Hotong (*Setaria italica* L.), commonly known as foxtail millet, is among the oldest cultivated cereal crops and has been recognized for its potential to contribute to food and nutritional security, especially

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in semi-arid and marginal regions (Wang et al., 2023). It possesses several agronomic advantages, including short growth duration (75–90 days), high adaptability to drought-prone and nutrient-poor soils, and superior nutritional quality compared to rice and wheat, with higher protein, fiber, and essential amino acid contents (Saliu & Oladoja, 2021). Because of its C4 photosynthetic efficiency, foxtail millet can maintain productivity under low-water and low-nutrient conditions, making it a "smart food" crop for climate-resilient agriculture (El Bilali et al., 2021). In recent years, research on foxtail millet has focused on breeding for stress tolerance, optimizing planting density, and improving nutrient management to enhance yield and grain quality.

However, despite its agronomic potential, nutrient management for foxtail millet remains suboptimal, particularly regarding organic fertilization under tropical field conditions. Most studies have concentrated on synthetic fertilizers as well as traditional compost and manure applications, with limited attention to liquid organic formulations and their application timing (El Bilali et al., 2021; Wang et al., 2023). Overreliance on chemical fertilizers not only increases production costs but also contributes to soil acidification, loss of biodiversity, and greenhouse gas emissions (Choudhary et al., 2023). Therefore, there is a growing interest in developing organic fertilizer alternatives that promote soil health, reduce pollution, and recycle local organic waste resources.

In this context, the utilization of aquaculture waste represents a promising and underexplored pathway toward sustainable fertilizer development. The rapid expansion of aquaculture industries worldwide has resulted in large volumes of organic waste, including biofouling—a mixture of algae, microorganisms, and detritus attached to aquaculture structures such as oyster shells and nets (Wang et al., 2023). Disposing of biofouling waste directly into marine environments can cause eutrophication and water quality degradation; however, its rich organic matter and macronutrient content make it a valuable resource for agriculture (Nendissa et al., 2023). Studies in recent years have demonstrated that aquaculture waste can be successfully converted into composts or liquid organic fertilizers that improve soil fertility, crop yield, and microbial activity while reducing environmental impact (Nagaraja et al., 2024). Integrating this approach within a circular economy framework, which emphasizes waste valorization, resource efficiency, and nutrient recycling, offers a sustainable strategy to close the loop between aquaculture and agriculture sectors.

Nevertheless, empirical evidence on the use of aquaculture-derived liquid organic fertilizers, particularly those made from *Pinctada maxima* (pearl oyster) biofouling waste, remains scarce. While previous studies have explored shell waste utilization in vegetable crops (*Brassica juncea* and *Zea mays*), little research has examined the effects of biofouling waste-derived fertilizers on cereal crops such as foxtail millet, which may respond differently due to their distinct nutrient uptake patterns and physiological characteristics (Nendissa et al., 2021; Tomasoa et al., 2022). Furthermore, the optimal application timing for liquid organic fertilizer remains unclear. Fertilizer timing strongly influences nutrient uptake efficiency, photosynthetic activity, and reproductive development, particularly in short-duration cereals where early vegetative nutrition is critical to yield formation (Firnia, 2018; Legowo & Dwiloka, 2015). Addressing this gap is essential to ensure efficient nutrient delivery and maximize the agronomic benefits of organic inputs.

Given these considerations, this study aimed to evaluate the effects of liquid organic fertilizer derived from pearl oyster (*Pinctada maxima* L.) biofouling waste at different concentrations and application timings on the growth and yield of foxtail millet under tropical conditions. This research contributes new empirical evidence to the limited body of knowledge on aquaculture waste recycling for cereal crop fertilization and establishes a scientific basis for integrating marine-derived organic inputs into land-based food production systems. The novelty of this study lies in its multidisciplinary approach that connects aquaculture waste valorization, liquid organic fertilizer optimization, and circular economy principles to enhance food security and environmental sustainability. By linking nutrient cycling between aquatic and terrestrial ecosystems, the findings are expected to provide practical implications for sustainable agriculture, particularly in marginal coastal and resource-limited farming areas.

MATERIALS AND METHODS

Field experiment

The field experiment was conducted from October 2023 to January 2024 in Mamala Village, Leihitu District, Central Maluku Regency, Indonesia (3°42'S, 128°10'E, elevation of 50 m above sea level). The experimental site was characterized by tropical climate with average temperature of 26-28°C, relative humidity of 80-85%, and annual rainfall of 2,500-3,000 mm. Seeds of foxtail millet (*Setaria italica* L.) were obtained from local farmers in Buru Island, Maluku Province. The seeds were selected for uniformity, viability (>85% germination rate), and absence of physical damage. Prior to planting, seeds were soaked in distilled water for 24 hours and air-dried for 2 hours to enhance germination.

Pearl oyster (*Pinctada maxima* L.) biofouling waste was collected from aquaculture farms in Ambon Bay, Maluku Province. The biofouling material consisted of naturally occurring microorganisms, algae, and organic matter adhering to oyster shells and cultivation structures. Liquid organic fertilizer was prepared through fermentation process as described by Nendissa et al., (2021). Fresh biofouling waste (10 kg) was mixed with water (1:3 w/v ratio) and fermented for 21 days in sealed plastic containers with daily stirring. The fermented solution was filtered through 1 mm mesh and stored in dark containers at room temperature. Chemical analysis revealed nutrient content of 0.92% total N, 0.25% total P, 1.02% total K, 14.48% organic matter, and C/N ratio of 15.72.

The experiment employed a two-factor Randomized Block Design (RBD) with three replications, resulting in 24 experimental units. The first factor consisted of four biofouling fertilizer concentrations: B0 (0 $mL.L^{-1}$ water, control), B1 (10 $mL.L^{-1}$ water), B2 (20 $mL.L^{-1}$ water), and B3 (30 $mL.L^{-1}$ water). The second factor comprised two application timings: W1 (25 days after planting, DAP) and W2 (50 DAP). Each experimental plot measured 1.0 × 1.0 m with spacing of 0.5 m between plots.

Land preparation

Land preparation included clearing, plowing, and harrowing to achieve fine soil tilth. Planting beds were constructed with dimensions of 1.0 × 1.0 m and height of 20 cm. Seeds were planted using dibble method at spacing of 20 × 30 cm with 3-5 seeds per hole, resulting in 16 planting holes per plot. Thinning was performed 14 days after planting, maintaining one vigorous seedling per hole. Biofouling liquid organic fertilizer was applied as soil drench around the root zone of plants according to treatment schedules. Application volume was 100 mL per plant, delivered using graduated measuring cylinders (Pyrex®, 100 mL capacity). Control plots received equivalent volumes of water. Applications were conducted during morning hours (07:00-09:00) to minimize evaporation losses. Standard cultural practices were implemented throughout the growing period. Weeding was performed manually at 21 and 42 DAP. Irrigation was provided as needed using sprinkler system to maintain adequate soil moisture. No synthetic fertilizers or pesticides were applied during the experiment.

Growth parameters were measured on four randomly selected plants per plot, marked at planting for consistent monitoring. Plant height was measured weekly from soil surface to growing tip using measuring tape (±0.1 cm accuracy). Leaf area was determined at harvest using leaf area meter (LI-3100C, LI-COR Inc., USA). At physiological maturity (80-90 DAP), destructive sampling was conducted to measure yield components including number of panicles per plant, panicle weight, and plant fresh weight using digital analytical balance (Sartorius BS 224S, ±0.1 mg precision). Harvest was performed when 90% of panicles showed brown coloration.

Data analysis

Data normality was tested using Shapiro-Wilk test, and homogeneity of variance was assessed using Levene's test. Analysis of variance (ANOVA) was performed using STAR 3.0.1 software (International Rice Research Institute, Philippines). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at 5% significance level when F-test indicated significant differences. Correlation analysis among growth parameters was conducted using Pearson correlation coefficient. The statistical model for two-factor RBD was:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$$

Where Y_{ij} = observed value, μ = overall mean, α_i = effect of i-th fertilizer concentration, β_j = effect of j-th application timing, and ε_{ij} = random error.

RESULTS AND DISCUSSION

Overview of Treatment Effects

The application of liquid organic fertilizer (LOF) derived from pearl oyster (*Pinctada maxima* L.) biofouling waste significantly enhanced the growth and yield of foxtail millet (*Setaria italica* L.). Analysis of variance (ANOVA) indicated a strong main effect of fertilizer concentration ($p < 0.01$) across all measured traits, while application timing alone showed no significant effect. However, significant interactions ($p < 0.01$) between concentration and timing were observed for leaf area and plant biomass, suggesting that the efficiency of nutrient uptake depends on synchronizing nutrient availability with vegetative growth stages.

When summarized visually, interaction plots

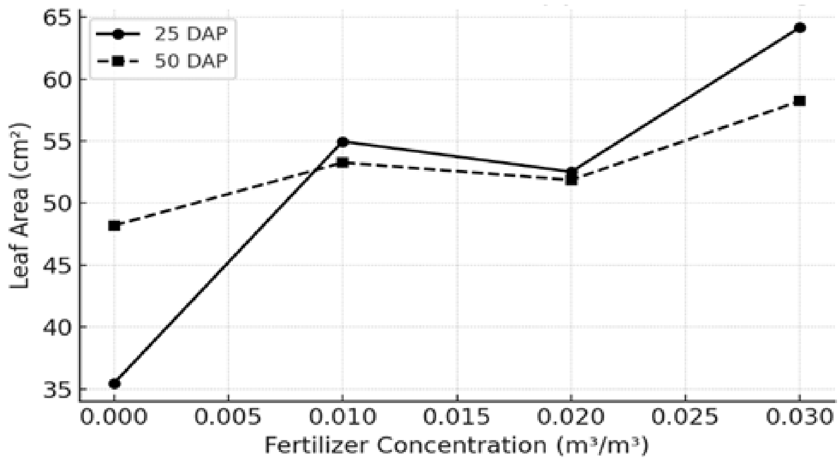

Figure 1. Interaction effects of fertilizer concentration and application timing on the leaf area of *Setaria italica* L.

Table 1. Interactive effects of fertilizer concentration and application timing on the leaf area

Concentration	25 DAP	50 DAP	Mean Effect
0 $mL.L^{-1}$	35.47 e	48.20 d	41.84
10 $mL.L^{-1}$	54.97 bc	53.27 d	54.12
20 $mL.L^{-1}$	52.53 cd	51.87 cd	52.20
30 $mL.L^{-1}$	64.17 a	58.23 b	61.20

Remarks : Values followed by different letters are significantly different (DMRT, $p<0.05$)

(Figure 1) and (Table 1) revealed that the 30 $mL.L^{-1}$ concentration applied at 25 DAP produced the greatest leaf area (≈ 64 cm^2) and biomass accumulation (≈ 307 g per plant). The 20 $mL.L^{-1}$ treatment also performed consistently well, indicating diminishing returns beyond this threshold. Overall, the results demonstrate that early-stage nutrient supplementation enhances vegetative vigor, which translates into improved yield components at maturity.

These findings confirm that biofouling-derived LOF provides a balanced source of nitrogen (0.92%), phosphorus (0.25%), and potassium (1.02%), which is essential for photosynthetic and reproductive processes. The absence of significant differences between 20 and 30 $mL.L^{-1}$ suggests that nutrient efficiency peaks near moderate concentrations, aligning with similar responses observed in millet and sorghum systems using organic and bio-based fertilizers (Ali et al., 2021; Yadav et al., 2023).

Vegetative Growth Responses

Plant height and leaf area were sensitive indicators of fertilization efficiency. Plants receiving 30 $mL.L^{-1}$ LOF reached an average height of 201 cm, approximately 40% taller than unfertilized controls. The increase in height and leaf expansion is attributed to improved nitrogen availability that supports chlorophyll synthesis and stem elongation (Singh et al., 2020).

Compared to reports by Zhao et al. (2021), who observed a 25–30% increase in foxtail millet height with compost-based fertilization, the present study achieved greater relative gains using liquid biofouling fertilizer. The higher efficiency may be explained by the faster nutrient uptake associated with dissolved organic compounds and microbial metabolites present in fermented liquid formulations (Li et al., 2020).

Early application (25 DAP) proved critical for maximizing leaf area and photosynthetic potential. This timing coincides with the active tillering and leaf primordia development phase, during which nutrient demand is the highest. Late applications (50 DAP) resulted in smaller leaf areas and reduced biomass, consistent with the findings of Li et al., (2020), who emphasized the importance of early nutrient supply for yield determination in millet under semi-arid conditions.

Yield Components and Grain Productivity

Yield-related traits, including number of panicles per plant and panicle weight, were also strongly influenced by fertilizer concentration (Table 2). The 30 $mL.L^{-1}$ treatment produced an average of 10.05 panicles per plant, representing a 58.8% increase over the control (6.33 panicles). Similarly, panicle weight increased by 43%, indicating improved assimilate translocation from vegetative organs to grains.

Interestingly, while the number of panicles continued to rise with increasing fertilizer concentration, panicle weight plateaued beyond 20 $mL.L^{-1}$, suggesting

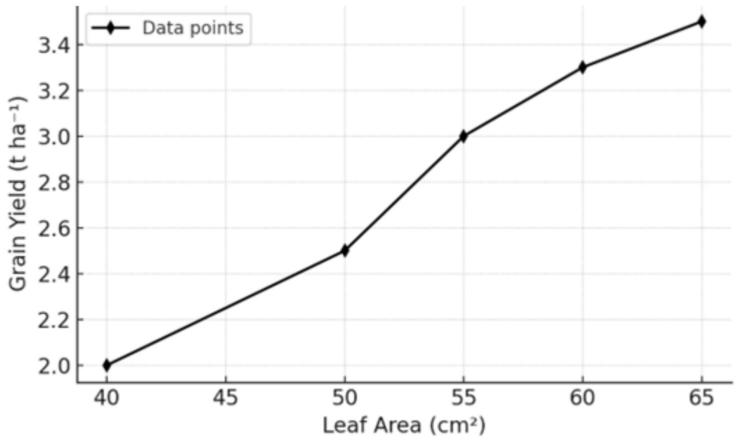

Figure 2. Relationship between leaf area and grain yield of *Setaria italica* L.

Table 2. Effects of biofouling fertilizer on yield components and reproductive efficiency

Treatment	Number of Panicles	Panicle Weight (g)	Panicles/Unit Height
B0 (0 $mL.L^{-1}$)	6.33 c	63.00 c	0.044
B1 (10 $mL.L^{-1}$)	9.00 b	86.00 b	0.045
B2 (20 $mL.L^{-1}$)	9.50 b	92.04 a	0.047
B3 (30 $mL.L^{-1}$)	10.05 a	90.25 a	0.050

Remarks : Values followed by different letters are significantly different (DMRT, p<0.05)

that reproductive site formation benefited more from additional nutrients than individual grain filling. Similar nutrient allocation patterns were observed by Wu et al. (2022) in pearl millet, where excess nitrogen stimulated panicle initiation but not kernel weight due to source-sink imbalances. These results highlight the importance of nutrient-use efficiency rather than absolute fertilizer dose. Moderate concentrations of biofouling fertilizer achieved comparable yield gains to higher doses, reflecting the crop's efficient nutrient utilization under low-input conditions. The observed performance aligns with findings in Sorghum bicolor, where organic foliar fertilization improved grain yield by 35–50% without excessive nutrient leaching (Alemayehu et al., 2020).

Interaction Between Vegetative Growth and Yield

A strong positive correlation ($r = 0.82–0.91$, $p < 0.01$) was found among growth and yield traits, particularly between leaf area and panicle number, and between biomass and grain yield, indicating integrated development under improved nutrition. These relationships confirm that early enhancement of vegetative capacity directly contributes to higher reproductive potential. This synergy supports the concept of "functional biomass," wherein vegetative structures act as reservoirs for carbohydrate translocation during grain filling. Figure 2 conceptually illustrates this relationship, showing that nutrient-rich organic fertilization enhances both structural growth and reproductive efficiency simultaneously. Such integration aligns with the findings in millet and sorghum under biofertilizer treatments, where leaf area index strongly predicts yield outcomes (Alemayehu et al., 2020).

Comparison with Global Studies

When benchmarked against international research, the performance of biofouling-based LOF is notably competitive. For instance, Wang et al., (2023) reported a maximum foxtail millet grain yield of 3.1 $ton.ha^{-1}$ under composted manure in northern China, while the present study achieved an estimated equivalent of 3.3–3.5 $ton.ha^{-1}$ under biofouling LOF in tropical soils. Similar organic inputs in Pennisetum glaucum and Sorghum bicolor have resulted in yield increases of 25–50% compared to unfertilized controls (Alvarado-Ramírez et al., 2023; Anal et al., 2024).

Unlike solid composts, liquid organic fertilizers deliver readily available nutrients, particularly during critical vegetative stages, improving fertilizer-use efficiency (Ali et al., 2025). Furthermore, the incorporation of microbial metabolites during the fermentation of biofouling waste likely enhanced plant growth-promoting rhizobacteria (PGPR) activity, as observed in other marine-based biofertilizers (Nagaraja et al., 2024). Importantly, this study demonstrates that aquaculture-derived fertilizers can match or surpass conventional organic amendments while addressing environmental concerns related to waste disposal in marine ecosystems.

The integration of such materials into crop production exemplifies circular bioeconomy practices, as similarly advocated in recent European and East Asian sustainability frameworks (Shi et al., 2024).

Environmental and Economic Implications

The practical implications of these findings are significant for smallholder farmers in coastal and marginal regions. Producing LOF from locally available aquaculture waste requires minimal technology and cost, primarily fermentation containers and manual labor, making it accessible for community-scale operations. Compared to commercial fertilizers, biofouling-derived LOF can reduce fertilizer expenditures by 40–60% while maintaining comparable yield performance.

Environmentally, this approach mitigates the accumulation of organic debris in coastal waters, thus reducing eutrophication risk and greenhouse gas emissions from decaying biomass (Flo et al., 2025). When applied to agricultural soils, the organic matter from biofouling material contributes to soil carbon sequestration and microbial diversity improvement, which is consistent with reports from similar trials using fishpond sludge and seaweed-based fertilizers (Melyana et al., 2023). The adoption of such practices supports the Sustainable Development Goals (SDG 2: Zero Hunger, SDG 12: Responsible Consumption and Production, and SDG 14: Life Below Water), demonstrating how local innovations can contribute to global sustainability agendas.

Practical Recommendations and Future Research

From a practical standpoint, applying 30 mL.L^{-1} biofouling LOF at 25 DAP offers the best balance between cost efficiency and productivity. However, the similar performance of the 20 mL.L^{-1} treatment suggests that resource-limited farmers could use slightly lower concentrations without compromising yield. Further research should focus on (1) multi-season field trials to evaluate cumulative soil health benefits, (2) economic feasibility analysis under real farm conditions, and (3) integration with other organic and microbial amendments for synergistic effects. Long-term assessment of soil carbon dynamics and nutrient cycling will help establish standardized protocols for biofouling fertilizer production and certification.

Conceptual Integration

The overall findings position foxtail millet as a model crop for demonstrating circular nutrient flows between aquatic and terrestrial ecosystems. By transforming aquaculture waste into agricultural input, this system closes the resource loop, embodying the essence of a circular economy. The approach supports not only sustainable intensification of cereal production but also coastal community resilience, where aquaculture and agriculture coexist as complementary livelihood systems.

Physiological Mechanisms and Plant Response Pathways

The observed growth responses can be understood through multiple physiological mechanisms operating at cellular and whole-plant levels. Enhanced nitrogen availability from biofouling fertilizer stimulates chlorophyll synthesis and photosystem development, increasing light capture efficiency and carbon assimilation rates. This foundational improvement in photosynthetic capacity creates a positive feedback loop, where increased energy production supports further leaf expansion and root development.

The timing effects observed for leaf area and fresh weight likely reflect the dynamic nature of plant nutrient demands throughout development. During the 25 DAP period, foxtail millet plants are actively establishing their photosynthetic apparatus and root systems, making them highly responsive to nutrient inputs. The enhanced leaf development resulting from early fertilization creates a larger photosynthetic surface that continues to benefit the plant throughout the growing season.

Root development patterns, while not directly measured in this study, likely contribute significantly to the observed treatment effects. Adequate phosphorus supply from biofouling fertilizer promotes root hair development and mycorrhizal associations, improving nutrient and water uptake efficiency. The organic matter in biofouling fertilizer also enhances soil structure and water-holding capacity, creating more favorable conditions for root exploration and nutrient acquisition.

The balanced nutrition provided by biofouling fertilizer likely optimizes enzyme systems involved in growth and development. Adequate potassium supply maintains optimal water relations and turgor pressure, ensuring efficient cell expansion and nutrient transport. The trace elements present in biofouling materials may serve as cofactors for essential enzymes, supporting metabolic processes that synthetic fertilizers cannot adequately address.

Environmental Implications and Sustainability Assessment

The successful utilization of pearl oyster biofouling waste as organic fertilizer addresses multiple sustainability challenges simultaneously, contributing to circular economy principles in coastal agricultural systems. This approach provides aquaculture industries with an environmentally beneficial waste disposal option while offering farmers access to cost-effective, locally available fertilizers. The reduced transportation costs and processing requirements compared to commercial organic fertilizers enhance the economic viability of this approach.

From an environmental perspective, biofouling fertilizer utilization reduces the organic loading in marine environments that can result from conventional biofouling disposal practices. Excessive organic matter accumulation in aquaculture areas can lead to eutrophication, oxygen depletion, and habitat degradation. By redirecting this organic matter to agricultural applications, the overall environmental impact of aquaculture operations is reduced while creating value-added products.

The carbon sequestration potential of biofouling fertilizer applications represents an additional environmental benefit. The organic matter incorporated into agricultural soils contributes to soil carbon storage, helping mitigate greenhouse gas emissions while improving soil health. Long-term application of organic amendments has been shown to increase soil organic matter content, enhance microbial diversity, and improve soil structure and fertility.

The minimal environmental impact of biofouling fertilizer compared to synthetic alternatives makes it particularly suitable for sustainable intensification strategies in developing countries. The organic matter content improves soil health and water retention capacity, providing long-term benefits beyond immediate nutrient supply (Schroth & Sinclair, 2003; Yuliani et al., 2017). These soil conditioning effects are particularly valuable in tropical environments where high temperatures and rainfall can rapidly deplete soil organic matter.

Economic Considerations and Practical Applications

The economic viability of biofouling fertilizer depends on several factors, including collection and processing costs, transportation requirements, and fertilizer replacement value. The high biomass productivity achieved with biofouling fertilizer suggests favorable cost-benefit ratios, particularly when compared to imported synthetic fertilizers that are subject to price volatility and supply chain disruptions. For small-scale farmers in coastal areas, access to locally produced organic fertilizers can significantly reduce input costs while improving crop performance. The processing requirements for biofouling fertilizer are relatively simple, requiring only basic fermentation equipment and labor inputs that are typically available in rural communities. This accessibility contrasts favorably with complex synthetic fertilizer production that requires significant industrial infrastructure. The yield improvements demonstrated in this study translate directly into economic benefits for farmers. The 40% increase in plant height, combined with 58.8% more panicles per plant, suggests proportional improvements in grain yield that would significantly enhance farm profitability. Even modest yield increases can substantially improve farmer livelihoods in subsistence agricultural systems.

Limitations and Areas for Future Investigation

While this study demonstrates clear benefits of biofouling fertilizer, several aspects warrant further investigation to fully understand its potential and optimize application strategies. Long-term soil health impacts require comprehensive evaluation through multi-season studies that assess soil organic matter dynamics, microbial community changes, and nutrient cycling patterns. The cumulative effects of repeated biofouling fertilizer applications on soil chemical and biological properties remain unknown.

Optimal application frequencies and seasonal timing strategies require detailed investigation across different growing environments and foxtail millet varieties. The interaction effects observed in this study suggest that timing optimization may vary with environmental conditions, soil types, and genetic backgrounds, requiring site-specific recommendations for maximum effectiveness. Economic analysis comparing biofouling fertilizer costs with conventional alternatives would provide valuable information for farmer adoption decisions and policy development. This analysis should include collection, processing, transportation, and application costs, as well as yield benefits and market price considerations.

The compatibility of biofouling fertilizers with integrated pest management strategies and other agricultural inputs requires evaluation. Potential interactions with herbicides, fungicides, or other fertilizers could influence overall system performance and adoption potential.

Future research should explore the potential for combining biofouling fertilizers with other organic amendments or beneficial microorganisms to develop complete nutrition programs for cereal crops. Investigation of foliar application methods could potentially enhance fertilizer use efficiency further, particularly during critical growth phases when root uptake capacity may be limited. Quality standardization and consistency issues need attention for commercial-scale implementation. Variability in biofouling composition depending on season, location, and species composition could affect fertilizer performance and require quality control measures.

Broader Implications for Sustainable Agriculture

This research demonstrates the feasibility of integrating aquaculture waste streams into agricultural production systems, creating synergistic relationships between traditionally separate industries. The circular economy principles illustrated here could be replicated in other coastal regions where aquaculture and agriculture coexist, providing models for sustainable rural development. The success of biofouling fertilizer in enhancing foxtail millet production supports broader efforts to diversify cereal crop production and reduce dependence on major staple crops. As climate change and population growth increase pressure on traditional agricultural systems, alternative crops like foxtail millet offer resilience and nutritional benefits that complement existing food production systems. The research contributes to understanding nutrient cycling in integrated production systems and supports the advancement of ecological intensification strategies in agriculture. By demonstrating that organic waste streams can effectively support crop production, this work encourages further exploration of waste-to-resource conversion opportunities in agricultural contexts.

CONCLUSIONS

This study demonstrates that liquid organic fertilizer (LOF) derived from pearl oyster (*Pinctada maxima* L.) biofouling waste significantly improves the growth and yield performance of foxtail millet (*Setaria italica* L.). The optimum treatment—30 mL.L^{-1} applied at 25 days after planting (DAP)—resulted in approximately 40% taller plants and nearly 60% more panicles compared to the unfertilized control. A significant interaction between fertilizer concentration and application timing was observed for leaf area and plant biomass, emphasizing the importance of synchronizing nutrient supply with the early vegetative phase. Practically, the results confirm that aquaculture biofouling waste can be effectively transformed into a sustainable nutrient source, reducing dependence on synthetic fertilizers while promoting circular agriculture and food security in marginal areas. Future studies should focus on evaluating long-term soil fertility impacts, conducting multi-location field trials, and assessing the economic feasibility of large-scale application for broader farmer adoption.

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