



Sustainable Agriculture: Assessing a Multi-Component Fermented Biostimulant for Improved Seedling Vigor

Dr. Khadatare Seema Vilas¹, Rahul Pujari², Samarth Waghmode², Prafulla Patil², Swati Zingade²

Department of Botany, Sangameshwar College, Solapur (Autonomous)

Abstract

The extensive reliance on synthetic fertilizers in modern agriculture has contributed to soil degradation, nutrient imbalance, decline in microbial diversity, and environmental pollution. To address these challenges, the present study investigates the efficacy of a **multi-component fermented organic biostimulant** developed from agro-industrial residues and household kitchen waste for enhancing early seedling growth. The biostimulant was prepared through controlled fermentation of sugarcane bagasse, mixed fruit peels, vegetable waste, rice water, coconut water, buttermilk, and jaggery. Its growth-promoting potential was evaluated using **fenugreek (*Trigonella foenum-graecum* L.)** under controlled conditions. The experiment was conducted in a Completely Randomized Design with two treatments: distilled water (control) and a 10% diluted fermented plant tonic. Growth parameters including shoot length, root length, total seedling length, fresh and dry biomass, and seedling vigor index were recorded five days after treatment. The treated seedlings exhibited significant improvement in all measured parameters compared to the control, with pronounced enhancement in root development, biomass accumulation, and vigor index. These results suggest that the fermented biostimulant improves nutrient availability and early physiological growth processes, likely mediated by beneficial microorganisms and bioactive compounds generated during fermentation. The study demonstrates the potential of waste-derived fermented biostimulants as cost-effective, eco-friendly alternatives to synthetic inputs, supporting sustainable agriculture and circular bioresource utilization.

Key words - Sustainable agriculture, biostimulants, seedling vigor, fermentation, organic amendments, soil health, and microbial diversity.

1. Introduction

In the past, modern farming has heavily relied on synthetic fertilizers to increase crop yields. However, the overuse and persistent application of these chemicals have resulted in environmental harm, including soil acidification, nutrient imbalances, a reduction in soil organic matter, and groundwater contamination (Ferreira et al., 2023). Initially, agrochemicals such as fertilizers and pesticides were considered beneficial to humans. However, scientific progress has revealed that these chemicals significantly damage the soil and, in turn, affect groundwater (Upadhyay et al., 2020). Rice fields subjected to intensive farming practices, characterized by excessive fertilizer and pesticide use, have exhibited increased salinity and soil acidity, further deteriorating soil health by restricting nutrient availability and impacting microbial communities. Over the last 50 years, agricultural intensification has primarily been driven by the extensive use of synthetic fertilizers, particularly those containing nitrogen (N), phosphorus (P), and potassium (K). Although these fertilizers have substantially boosted crop yields, their prolonged and excessive application

has led to significant ecological and agronomic issues (Oro et al., 2024). These include soil acidification, nutrient imbalances, a reduction in soil organic matter, disturbances in soil microbial diversity, contamination of groundwater, and the emission of greenhouse gases. (Currently, a wide range of agrochemicals, including herbicides, fungicides, insecticides, pneumaticides, molluscicides, and specific chemical fertilizers, are applied without adequate regulation (Hossain et al., 2022). The prolonged and extensive use of synthetic fertilizers and pesticides has demonstrably harmed soil health by altering essential physicochemical properties and reducing microbial diversity—both of which are crucial for nutrient cycling and soil structure stability. The application of chemical nitrogen fertilizers can cause soil acidification and nutrient imbalances, which in turn decrease organic matter and negatively affect beneficial soil organisms. (Meena et al., 2020)

Furthermore, the continuous use of pesticides and insecticides can negatively affect non-target soil organisms, such as earthworms, mycorrhizal fungi, and beneficial bacteria, leading to a decline in soil fertility and resilience. (Imran & Ortas, 2025). Agricultural chemicals often seep into both surface and groundwater systems, leading to nitrate contamination and pesticide residues in drinking water sources. (Sebilo et al., 2013). Long-term exposure to these residues through food and water has been associated with endocrine disruption, neurodevelopmental issues, reproductive toxicity, and a heightened risk of cancer in humans. (Mostafalou & Abdollahi, 2013; Kim et al., 2017; Mandal, 2022). (Nieder et al., 2018) The accumulated evidence emphasizes the urgent requirement to adopt sustainable and ecologically sound nutrient management practices to protect soil ecosystems and ensure public health.

The prolonged and widespread use of chemical fertilizers, pesticides, and insecticides has been widely documented to negatively impact soil health and pose serious risks to human health. Synthetic nitrogen fertilizers, particularly those derived from urea and ammonium, contribute to soil acidification, disrupt nutrient balance, and reduce soil organic carbon (SOC) levels. This, in turn, affects soil microbial communities, which are essential for nutrient cycling and plant growth (Xing et al., 2025). Consistent fertilizer application without the addition of organic amendments leads to a decline in soil biodiversity and enzyme activity, ultimately compromising long-term soil fertility.

In conjunction with the intensification of agriculture, rapid urban growth and the expansion of agro-industrial activities have resulted in the generation of substantial amounts of biodegradable waste. This includes materials such as fruit peels, vegetable scraps, sugarcane bagasse, and starchy waste, including rice water. Improper disposal of this waste contributes to methane emissions and environmental degradation (Haque et al., 2021). Transforming biodegradable waste into valuable agricultural products is a sustainable approach that aligns with the principles of a circular economy, where waste is repurposed into productive systems instead of being thrown away (Paradelo et al., 2023)

Organic amendments derived from plant residues have been shown to enhance soil microbial biomass, elevate enzymatic activity, and accelerate nutrient mineralization rates. Biofertilizers derived from fermentation and liquid organic solutions, including compost teas and plant extracts, have shown promise in enhancing plant growth, improving nutrient absorption efficiency, and increasing resistance to biotic stress. (Fermentation processes decompose complex organic materials into simpler, more accessible compounds, thereby encouraging the growth of beneficial microorganisms that aid in nutrient solubilization and phytohormone production (Omokaro et al., 2024).

Natural sources, such as coconut water, are rich in cytokinins and growth-enhancing compounds that promote cell division and vegetative development (Akhtar et al., 2020). Likewise, lactic acid bacteria present in fermented dairy products, such as buttermilk, can boost microbial diversity and aid in the production of organic acids, enhancing nutrient solubility in soil environments (Wan-Mohtar et al., 2023). Jaggery, an unrefined traditional sugar, provides a carbon source that invigorates microbial metabolism during fermentation, thereby accelerating biochemical transformation processes.

1.2 Research Gap

Despite extensive research on the use of organic manures, compost extracts, and biofertilizers to enhance plant growth, a notable gap exists in studies focusing on the creation of a standardized multi-component fermented biostimulant. This biostimulant is derived from agro-industrial residues, such as sugarcane bagasse, and a variety of kitchen wastes, including fruit peels, vegetable waste, rice water, buttermilk, coconut water, and jaggery. Current research predominantly examines single-source organic inputs, such as vermicompost, panchagavya, and compost tea, rather than exploring integrated formulations incorporating carbon-rich lignocellulosic biomass, natural phytohormone sources, and microbial inoculants within a cohesive fermentation system.

Moreover, quantitative data evaluating the synergistic effects of these composite organic formulations on plant growth metrics in controlled experimental settings are lacking. The combined effects of naturally occurring lactic acid bacteria (from buttermilk), sugar-based microbial activation (from jaggery), and substrates rich in plant hormones (such as coconut water) on nutrient solubilization, microbial growth, and biomass production have not been thoroughly investigated.

A significant issue is the lack of standardized preparation methods, assessments of reproducibility, and statistical validation of growth responses. Many traditional formulations are used empirically in small-scale agriculture, yet they have not undergone thorough scientific evaluation, replication, or comparative statistical analyses with untreated controls.

This study aims to address this gap by developing a composite fermented biostimulant from various agro-kitchen waste materials, utilizing a controlled experimental setup with replicates, and quantitatively assessing its effects on plant growth and biomass yield. This research connects traditional organic methods with the development of sustainable agricultural inputs supported by scientific evidence.

1.3 Problem Statement

The increasing reliance on synthetic fertilizers in contemporary agriculture has resulted in soil degradation, nutrient imbalances, diminished microbial diversity, and environmental contamination. Although organic options, such as compost, vermicompost, and liquid biofertilizers, are available, many small-scale farmers and households lack access to standardized, affordable, and scientifically proven formulations produced from readily available waste materials.

Large amounts of agro-industrial byproducts, such as sugarcane bagasse, and household kitchen waste, including fruit peels and vegetable scraps, are produced but often remain underutilized or improperly discarded, contributing to environmental issues. Although traditional organic fermentation methods exist, they are frequently non-standardized and their benefits for growth are seldom supported by controlled experiments or statistical evidence.

Consequently, it is crucial to develop a scientifically designed, reproducible, and cost-effective organic plant biostimulant derived from a combination of agricultural and kitchen waste materials, and to quantitatively assess its impact on plant growth in controlled environments.

1.4 Justification

This study promotes sustainable agriculture through a fermented organic biostimulant derived from agro-industrial and kitchen waste, supporting UN Sustainable Development Goals 2, 12, 13, and 15. Reducing synthetic fertilizer use can mitigate soil degradation and pollution. This formulation offers a low-cost, decentralized solution for household-level organic farming implementation, aligning with policies focused on nutrient management and waste utilization. The study integrates sustainable agriculture, waste valorization, and rural development within relevant policy frameworks.

Fenugreek (* *Trigonella foenum-graecum* * L.) is a leguminous crop valued for its nutritional and medicinal properties. Early seedling establishment is crucial for crop performance. This study evaluated the effect of a fermented organic plant tonic on fenugreek seedling growth under controlled conditions.

2. Material And Method

2.1 Preparation of Fermented Organic Plant Tonic

Materials

The plant tonic was prepared using agro-industrial and household biodegradable waste.

The components included sugarcane bagasse (100 g),

Mixed fruit peels (banana, orange, and papaya; 200 g),

Vegetable waste (200 g),

Coconut water (200 ml),

Buttermilk (200 ml),

Rice water (300 ml),

Jaggery (50 g), and

Distilled water (2 L) was used for

A 5-liter plastic fermentation container, along with a lid and muslin cloth for filtering, was utilized.

2.2 Substrate Preparation

Fruit peels and vegetable waste were thoroughly washed with clean water to remove soil and contaminants. Subsequently, the materials were chopped into small pieces, approximately 1–2 cm in size, to increase their surface area and facilitate microbial degradation. Sugarcane bagasse was shredded to accelerate its decomposition.

2.3 Fermentation Process

All solid materials, including sugarcane bagasse, fruit peels, and vegetable waste, were placed in a clean plastic container. To promote microbial growth, 50 g of jaggery was dissolved in lukewarm water and added as a carbon source.

Subsequently, 200 mL of coconut water, 200 mL of buttermilk, 300 mL of rice water, and 2 L of distilled water were added to the mixture. The components were then thoroughly blended using sterile wooden stirrers.

The container was draped with muslin cloth to facilitate airflow and loosely sealed to prevent contamination while allowing gas exchange. Fermentation occurred at room temperature (25–35°C) in a shaded location over 7–10 days. The mixture was manually stirred once daily to ensure consistent microbial activity and prevent anaerobic spoilage.

2.4 Filtration and Collection

Once fermentation was complete, as indicated by a slightly sour odor and the breakdown of solid materials, the mixture was strained through sterile muslin. The resulting liquid was labeled as the fermented organic plant tonic.

2.5 Storage Conditions

The filtered extract was stored in sterilized, airtight containers at room temperature, protected from direct light exposure. It was used within 30 days to maintain optimal bioactivity.

Application of Fermented Plant Tonic

The fermented plant tonic was filtered and diluted with distilled water to achieve a 10% concentration (1:10 v/v) prior to application. This study assessed the impact of the fermented organic plant tonic on the initial growth of *Trigonella foenum-graecum* L. seedlings under controlled conditions. A Completely Randomized Design (CRD) was employed, utilizing two treatments: T0 (control, treated with distilled water) and T1 (10% fermented plant tonic solution). For the T1 treatment group, the diluted tonic was applied as a soil drench immediately following the transplantation of uniformly germinated seedlings. The control group (T0) received an equivalent volume of distilled water to maintain consistent experimental conditions. The application was conducted under controlled environmental conditions (25–30°C), with measures taken to prevent waterlogging. No additional fertilizers or growth regulators were utilized during the experiment to isolate any observed effects attributable solely to the plant tonic. Growth measurements were taken five days post-germination.

3. Result

3.1 Nutrient Availability In Fermented Organic Plant Tonic

Nutrient Component	Source in Fermented Material	Role in Plant Growth
Nitrogen (N)	Vegetable waste, fruit peels, buttermilk	Enhances vegetative growth, leaf development, and protein synthesis
Phosphorus (P)	Fruit peels, rice water	Promotes root development, flowering, and energy transfer
Potassium (K)	Banana peels, coconut water	Improves photosynthesis, disease resistance, and fruit quality
Calcium (Ca)	Buttermilk, vegetable waste	Strengthens cell walls and improves plant structural integrity
Magnesium(Mg)	Vegetable waste, rice water	Essential for chlorophyll formation and photosynthesis
Iron (Fe)	Sugarcane bagasse, vegetable waste	Involved in chlorophyll synthesis and enzyme activity
Zinc (Zn)	Fruit peels, vegetable waste	Supports enzyme activation and hormone production
Manganese (Mn)	Sugarcane bagasse, plant residues	Assists in photosynthesis and metabolic processes

Beneficial Microorganisms	Buttermilk, rice water	Improve nutrient availability and soil microbial healthy
Plant Growth Hormones (Auxins, Cytokinins, Gibberellins)	Produced during fermentation	Stimulate root growth, cell division, and shoot elongation

3.2 Parameters observed in after 5 days (Fenugreek seedlings)

To assess the impact of the fermented organic plant tonic on seedling growth at 5 days after germination (5 DAG), the following criteria were used:

Shoot Length (cm)

Root Length (cm)

Total Seedling Length (cm)

Fresh Weight (g per 10 seedlings)

Dry Weight (g per 10 seedlings)

Seedling Vigour Index (based on total seedling length)

3.3 Results at 5 Days After Treatment (5 DAT)

Table: Effect of 10% Fermented Organic Plant Tonic on Early Seedling Growth of Fenugreek (5 DAT)

Parameter	T0 (Control)	T1 (10% Plant Tonic)	% Increase Over Control
Shoot Length (cm)	5.2 ± 0.3	6.9 ± 0.4	+32.7%
Root Length (cm)	1.6 ± 0.2	2.6 ± 0.2	+62.5%
Total Seedling Length (cm)	6.8 ± 0.3	9.5 ± 0.4	+39.7%
Fresh Weight (g/10 seedlings)	0.72 ± 0.05	1.05 ± 0.07	+45.8%
Dry Weight (g/10 seedlings)	0.11 ± 0.01	0.17 ± 0.01	+54.5%
Vigour Index*	68	95	+39.7%

Calculation of Vigour Index

An equal number of seedlings (10 per replicate) were used.

SVI = Mean Total Seedling Length × 10

Control: 6.8 × 10 = 68

Treatment: 9.5 × 10 = 95



T1 - Treated Group



T0 - Control

4. Discussion

The observed improvement in seedling growth in the treated plants suggests that the fermented organic tonic acted as a biostimulant. A more significant increase in root length indicates an enhanced capacity for nutrient and water uptake, likely leading to greater biomass accumulation. Fermentation of organic materials may produce beneficial metabolites, micronutrients, and growth-promoting substances that activate early physiological processes in plants. Consistent progress from 5 to 10 days post-treatment demonstrates sustained positive effects during the initial growth phase. These results highlight the potential of fermented organic formulations as sustainable growth-enhancing inputs for crop production systems.

Building on observed biostimulant effects, the fermented organic plant tonic likely enhanced microbial activity in the rhizosphere, facilitating improved nutrient solubilization and availability for plant uptake. The introduction of beneficial microorganisms, such as lactic acid bacteria, via buttermilk and rice water may have contributed to the suppression of soil-borne pathogens and promotion of plant health. Furthermore, bioactive compounds—including plant hormones (auxins, cytokinins, and gibberellins)—generated during fermentation probably stimulated cell division, elongation, and differentiation, thereby accelerating seedling development.

The significant increase in root length is particularly important because it suggests improved root architecture and function, facilitating enhanced water uptake and anchorage. This effect can enhance plant resilience to abiotic stresses and support higher nutrient acquisition efficiency. Furthermore, enhanced shoot growth and biomass accumulation indicated a positive influence on photosynthetic capacity and overall metabolic activity.

These findings align with sustainable agriculture goals by demonstrating that multi-component fermented organic formulations can serve as effective and eco-friendly alternatives to synthetic fertilizers and growth regulators. Furthermore, utilizing agro-industrial and kitchen waste as raw materials promotes circular economy principles by valorizing waste streams and reducing environmental pollution.

Future research should focus on characterizing microbial consortia within fermented tonics and elucidating the specific biochemical pathways involved in plant growth promotion. Detailed profiling of phytohormones and secondary metabolites will help clarify the mechanisms underlying these observed effects. Field validation across diverse crops and environmental conditions is essential to establish practical recommendations regarding dosage, application methods, and integration into existing nutrient management systems.

Overall, this study supports the potential of fermented organic biostimulants as sustainable inputs that enhance early plant growth, improve soil health, and contribute to environmentally responsible agricultural practices.

5. Conclusion

The application of a 10% fermented organic plant tonic markedly enhanced the early growth stages of fenugreek seedlings, as evidenced by increased shoot and root lengths, total seedling length, fresh and dry weights, and an improved vigor index. The root system exhibited significant enhancement, indicating stronger early establishment. This study underscores the potential of fermented organic formulations as effective, eco-friendly biostimulants. Such inputs could play a crucial role in advancing sustainable and organic agriculture by encouraging robust early crop growth without relying on synthetic growth enhancers.

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Conflict of Interest:

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

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