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Optimization of Fermented Bio-Regulators Applied to Soil and Leaves for Sustainable Okra (*Abelmoschus esculentus*) Production

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ABSTRACT

The study aims to develop eco-friendly alternatives to conventional fertilization for the sustainable intensification of vegetable production. This research assessed the impact of locally produced fermented amendments and methods of their application on okra, *Abelmoschus esculentus*. The experiment employed a randomized complete block design with nine treatments comparing four fermented preparations (plant juice, fruit juice, fish amino acids, and eggshells) applied through subsurface or foliar methods against conventional soil test recommendations. Bio-amendments demonstrated superior performance in maintaining soil nutrient status, with fermented amendments maintaining higher soil organic matter (3.32%) than conventional fertilization (3.18%). Foliar application of fermented fruit juice (FFJ) produced the tallest plants (62.32 cm at 90 DAS), while FFJ-subsurface significantly accelerated flowering (30.50 days). Fish amino acid foliar application yielded the highest number of marketable fruits (3.00), while FFJ-foliar treatment achieved the maximum marketable fruit weight (72.50 g). Bio-amended treatments also influenced fruit nutritional composition, with FAA-subsurface and FPJ-foliar treatments resulting in significantly lower fiber content (24.35%) compared to conventional fertilization (24.46%), while maintaining consistent levels of ash (6.37-6.42%), protein (10.38-10.42%), and fats (1.38-1.41%). Results demonstrate that locally sourced fermented bio-amendments can effectively match or exceed conventional fertilization while supporting soil health, particularly when applied through appropriate delivery methods. This research provides practical guidance for sustainable okra production while advancing the understanding of bio-amendment delivery system optimization.

Keywords: Fermented bio-amendments, Foliar application methods, Subsurface fertilization, Fish amino acids, Sustainable agriculture

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Sürdürülebilir Bamya (*Abelmoschus esculentus*) Üretimi İçin Toprak Altı ve Yaprak Uygulamalı Fermente Biyo-Düzenleyicilerin Optimizasyonu

ÖZ

Çalışma, sebze üretiminin sürdürülebilir yoğunlaştırılması için geleneksel gübreleme yöntemlerine çevre dostu alternatifler geliştirmeyi amaçlamaktadır. Bu araştırmada, yerel olarak üretilen fermente düzenleyicilerin ve bunların bamya (*Abelmoschus esculentus*) üzerindeki uygulama yöntemlerinin etkisi değerlendirilmiştir. Deney, rastgele tam blok deneme deseni kullanılarak dokuz farklı uygulamayı içermektedir. Dört fermente hazırlık (bitki suyu, meyve suyu, balık amino asitleri ve yumurta kabukları), toprak altı veya yaprak uygulama yöntemleriyle, geleneksel toprak analizine dayalı gübreleme önerileriyle karşılaştırılmıştır. Biyo-düzenleyiciler, toprak besin durumunu koruma açısından üstün performans göstermiş ve fermente düzenleyiciler, geleneksel gübrelemeye göre daha yüksek organik madde içeriğini (3,32%) sağlamıştır (geleneksel gübreleme: 3,18%). Fermente meyve suyu (FFJ) yaprak uygulaması, en uzun bitkileri üretmiştir (90. gün sonunda 62,32 cm), FFJ-toprak altı uygulaması ise çiçeklenmeyi önemli ölçüde hızlandırmıştır (30,50 gün). Balık amino asidi yaprak uygulaması, en yüksek pazar değerindeki meyve sayısını (3,00) sağlamış, FFJ-yaprak uygulaması ise en ağır pazar değerindeki meyve ağırlığını (72,50 g) elde etmiştir. Biyo-düzenleyici uygulamaları, meyve besin bileşimini de etkilemiştir. FAA-toprak altı ve FPJ-yaprak uygulamaları, geleneksel gübrelemeye (24,46%) kıyasla önemli ölçüde daha düşük lif içeriği (24,35%) sağlamış, aynı zamanda kül (6,37-6,42%), protein (10,38-10,42%) ve yağ (1,38-1,41%) seviyelerini tutarlı bir şekilde korumuştur. Sonuçlar, yerel kaynaklı fermente biyo-düzenleyicilerin uygun uygulama yöntemleriyle kullanıldığında geleneksel gübrelemeyle eşit veya üstün performans gösterebildiğini ve toprak sağlığını desteklediğini ortaya koymaktadır. Bu araştırma, sürdürülebilir bamya üretimi için pratik rehberlik sağlamakta ve biyo-düzenleyici uygulama sistemlerinin optimizasyonuna ilişkin anlayışı geliştirmektedir.

Anahtar Kelimeler: Fermente biyo-düzenleyiciler, Yaprak uygulama yöntemleri, Toprak altı gübreleme, Balık amino asitleri, Sürdürülebilir tarım

1. Introduction

Modern agriculture worldwide is under mounting pressure to produce more food to meet the demand while reducing chemical inputs and environmental degradation. Modern conventional farming practices are primarily based on synthetic fertilizers that are inherently hazardous to human health and gradually deplete the soil [1]. This challenge has been felt in okra (*Abelmoschus esculentus*) production driven by intensive practice and depending much on chemical fertilizer, hence affecting the quality of soil and causing a high cost of production [2, 3]. The quest for sustainable alternatives has sparked a ray of hope in the form of organic bio-amendments, particularly fermented preparations [4]. These alternatives have shown the potential to enhance nutrient availability and soil biological activity, matching or surpassing mineral fertilization's effectiveness [5]. Importantly, these bio-based solutions hold particular promise for small-scale farmers, offering potential cost savings and promoting circular agricultural principles [6].

However, significant knowledge gaps exist regarding the optimal formulation and application of locally sourced bio-amendments. While studies have explored various organic inputs individually, including fish waste [7], plant materials [8], and fermented preparations [4], limited research has systematically compared their effectiveness when delivered through different application methods. The choice between subsurface and foliar application represents a critical knowledge gap, as each method influence nutrient availability and plant uptake patterns differently [9, 10].

This research addresses these gaps by integrating traditional fermentation techniques with modern application methods. The study uniquely combines locally available materials—including plant residues, fish waste, and eggshells—with a systematic comparison of subsurface and foliar application techniques. This approach aligns with emerging evidence that the application method significantly influences amendment effectiveness [32, 43] while supporting principles of sustainable intensification. The significance of this research extends beyond immediate agronomic benefits. With its comprehensive assessment of soil health, plant growth, and fruit quality parameters, this study provides a robust and reliable evaluation of sustainable okra production systems. By evaluating locally sourced bio-amendments, the research contributes to circular agriculture principles and offers potential economic advantages for small-scale farmers.

This research tests two fundamental hypotheses about bio-amendment effectiveness in okra production systems. First, we hypothesize that organic bio-amendments, when applied through optimized delivery methods, can match the performance of conventional fertilization practices while enhancing overall system sustainability. This builds on emerging evidence that fermented organic amendments can yield comparable mineral fertilization yields while improving soil biological properties. Second, we hypothesize that fertilizer application methods significantly influence crop response patterns, recognizing that nutrient delivery pathways can substantially affect plant uptake efficiency and growth responses. This research pursues several interconnected objectives by systematically evaluating different bio-amendments and application techniques. The primary aim is to determine how fermented bio-amendments (FPJ, FFJ, FAA, and FE) and their application methods affect soil chemical properties and plant growth parameters and to compare the effectiveness of subsurface versus foliar spray application methods for each bio-amendment type. The study also assesses how different bio-amendments and application methods influence fruit quality characteristics and the economic viability and sustainability implications of different treatment combinations.

2. Material and Method

2.1. Study locale and experimental design

The study was conducted from November 15, 2022, to February 28, 2023, at the Surigao del Norte State University (SNSU) Mainit Campus Demonstration Farm (9°31’48 “N, 125°30’36 “E), situated at an elevation of 42 meters above sea level. According to USDA Soil Taxonomy 2022, the soil is classified as Typic Hapludalf, with a silty loam texture and near-neutral pH. The site experiences evenly distributed rainfall (average 2.5 mm/day) during the wet season from May to October.

The experiment utilized a Randomized Complete Block Design (RCBD) with nine treatments: T1 (soil test recommendation - STR), T2 (FPJ – subsurface application), T3 (FFJ - subsurface application), T4 (FAA – subsurface application), T5 (FE – subsurface application), T6 (FPJ – foliar spray), T7 (FFJ – foliar spray), T8 (FAA – foliar spray), and T9 (FE – foliar spray). Each treatment was replicated four times, creating 36 experimental units of 2 × 2 m each. The study used a Smooth Green variety of okra (*Abelmoschus esculentus* L. Moench). Seeds were sown on November 15, 2022, with eight plants per experimental unit (2 seeds per hill, later thinned to one), maintaining 80 cm between furrows and 50 cm between plants, resulting in 32 plants per treatment across all replications.

2.2. Soil sampling and analysis

Initial soil sampling was conducted on November 1, 2022, using a 10-cm diameter soil probe (AMS Inc., American Falls, ID, USA). Each experimental unit collected ten soil cores at a depth of 15 cm in a zigzag pattern. Samples were homogenized to create composite samples for analysis. Post-harvest soil sampling was performed on March 1, 2023, following identical spatial sampling patterns but collecting separate samples from 0-10 cm and 10-15 cm depths to assess vertical nutrient distribution. All soil samples were air-dried, ground, and passed through a 2-mm sieve before analysis. Soil pH was determined in a 1:2.5 soil water suspension using a calibrated pH meter [11]. Soil organic matter (OM) was analyzed using the Walkley-Black chromic acid wet oxidation method [12]. Available phosphorus was extracted using the Olsen method for neutral to alkaline soils, with phosphorus concentration determined colorimetrically using the molybdenum blue method [13]. Available potassium was extracted using 1N ammonium acetate at pH 7.0 and measured using flame photometry [14]. All analyses were performed at the Department of Agriculture Soil Analytical Laboratory, Butuan City, Philippines.

2.3. Preparation of fermented amendments

Raw materials were sourced from the Mainit Public Market on November 8, 2022. Plant materials included Alugbati (*Basella alba*), Water spinach (*Ipomoea aquatica*), Sweet potato tops (*Ipomoea batatas*), Squash (*Cucurbita maxima*), Watermelon (*Citrullus lanatus*), and ripe Banana (*Musa acuminata*). Materials were washed and cut into 2.5 cm pieces.

Fermented Plant Juice (FPJ) was prepared by combining equal weights of chopped Alugbati, Water spinach, and sweet potato tops with molasses (1:1 w/w ratio). Fermented Fruit Juice (FFJ) was prepared similarly using banana, squash, and watermelon. Fish Amino Acids (FAA) were produced using fresh fish viscera and molasses (1:1 w/w); for Fermented Eggshells (FE), crushed chicken eggshells were mixed with molasses (1:1 w/w). Each mixture was fermented in sterilized 4L glass containers at 25±3°C. Plant-based media (FPJ, FFJ) were fermented for 7 days following modified protocols from Joshi and Rana (2009). Animal-based materials (FAA, FE) were fermented for 15-20 days.

2.4. Amendment application and irrigation

Treatments were applied weekly from November 22, 2022, to February 21, 2023. Fermented preparations were diluted (10 mL/L water) before application. The subsurface application involved delivering 250 mL of solution per plant directly to the root zone using calibrated watering cans with modified nozzles. Foliar spray applications were conducted using backpack sprayers with cone nozzles, applying the same volume per plant to achieve complete canopy coverage.

Irrigation was provided twice weekly using drip lines for subsurface treatments and overhead sprinklers for foliar treatments, maintaining soil moisture at field capacity based on tensiometer readings. The control treatment (STR) fertilization based on soil test recommendations of 3 bags of Ammosul/ha 10 days after transplanting (DAT) and one bag of Urea/ha at 30 DAT.

2.5. Crop management and data collection

Standard agronomic practices followed the Philippines National Okra Production Guide (2021). Plant height measurements were taken 30, 60, and 90 days after sowing. Reproductive development was monitored daily. Harvest began 45 days after sowing and continued thrice weekly until February 28, 2023. Fruits were harvested at commercial maturity (6-8 cm length) and sorted into marketable and non-marketable categories based on the Philippine National Standards for Fresh Vegetables (PNS/BAFS 40:2014).

2.6. Fruit nutrient analysis

Mature okra fruits were harvested at commercial maturity, cleaned, and prepared for nutrient analysis following Cunniff and Washington protocols [15]. Samples were analyzed in triplicate for ash, fiber, protein, and fat content. Ash content was determined using the dry ashing method by incinerating samples in a muffle furnace at 550°C until constant weight was achieved [16]. Crude fiber content was analyzed using the Weende method [17], involving sequential acid and alkaline digestion, followed by ashing of the residue [18].

Total protein content was determined using the Kjeldahl method, which involved digesting samples with concentrated sulfuric acid, followed by distillation and titration. The nitrogen content was multiplied by a conversion factor of 6.25 to obtain crude protein percentage [19]. Fat content was measured using the Soxhlet extraction method with petroleum ether as the extraction solvent [20]. All analyses were performed at the Department of Agriculture Feed Analytical Laboratory, Butuan City, Philippines.

2.7. Statistical analysis

All data was tested for normality using the Shapiro-Wilk test, and homogeneous variances were confirmed using Levene's test before the variance analysis. One-way ANOVA was utilized for post-harvest soil data and nutrient contents of okra fruits, followed by Tukey's test. A non-parametric Friedman Test was employed for plant height, days to flowering, and fruiting. All statistical analyses were carried out using SPSS Version 26 software. Statistical significance was determined at $p<0.05$ for all tests, and data are presented as mean ± standard error of replicates.

3. Results and Discussion

3.1. Pre-planting and post-harvest soil nutrient

Bio-amendment treatments demonstrated superior performance in maintaining and enhancing soil nutrient status compared to conventional STR treatment (Table 1). Treatments using fermented amendments maintained higher soil organic matter (3.32%) compared to STR (3.18%), with FAA-subsurface and FE-foliar treatments achieving the highest potassium levels (1345.44 ppm and 1345.59 ppm respectively). This effectiveness aligns with previous research showing that organic amendments enhance soil properties through multiple mechanisms [21, 1]. The stability of soil pH across treatments (5.91-6.11) indicates that bio-amendments maintain favorable conditions for nutrient availability and microbial activity. This finding corresponds with research demonstrating that organic amendments support consistent pH levels crucial for soil health [22]. Additionally, the maintained phosphorus levels (41.84-41.97 ppm) across treatments suggest effective nutrient cycling, though this contrasts with some studies reporting higher available P in organic systems [23].

The enhanced potassium availability under bio-amendment treatments indicates their effectiveness in improving soil K content. Recent research supports this finding, demonstrating that organic amendments can significantly increase various forms of potassium in surface soil layers [24]. Furthermore, the sustained organic matter levels under bio-amendments suggest potential long-term benefits for soil health, supporting findings about the superiority of organic practices in maintaining soil properties [25]. The effectiveness of fermented amendments specifically relates to their ability to improve soil microbial activity while maintaining crop yields comparable to mineral fertilization. Studies have shown that fermented organic amendments contain beneficial microbes capable of solubilizing soil nutrients [4, 5]. However, the full benefits of organic management require extended periods, as significant differences in soil properties typically emerge after 2-3 years of consistent application [26].

3.2. Growth, number of days to 50% flowering and 50% fruiting

3.2.1. Growth measurements of okra plants

Treatment effects on plant height showed progressively increasing differentiation over time, with statistical significance strengthening from 30 DAS ($p = 0.042$) to 90 DAS ($p < 0.001$) (Table 2). FFJ-foliar treatment consistently produced the tallest plants across all measurement periods (12.63 cm, 23.83 cm, and 62.32 cm at 30, 60, and 90 DAS respectively), while FFJ-subsurface resulted in the shortest plants at later stages (37.43 cm at 90 DAS). This temporal pattern suggests cumulative impacts of both ferment type and application method on growth patterns, supporting findings that nutrient elements progressively influence plant growth through multiple pathways [27]. The contrasting performance between foliar and subsurface applications highlights the crucial role of application method in treatment effectiveness. FFJ-foliar's superior performance aligns with research showing that foliar applications are particularly effective when timed to meet specific vegetative growth stages [28]. Moreover, studies have demonstrated that foliar application can be nearly as effective as soil application in influencing crop growth parameters [29]. The temporal development of treatment effects reflects distinct physiological mechanisms at each growth stage. Early phase differences (30 DAS: 10.69-12.63 cm) were relatively minor, suggesting initial nutrient availability was less treatment-dependent [21]. Mid-growth phase variations (60 DAS: 18.37-23.83 cm) increased as nutrients were progressively released from fermented amendments [4]. The dramatic differences at 90 DAS (37.43-62.32 cm) confirm that fermented amendments require time to fully establish their beneficial effects [5].

Table 1. Pre-planting and post-harvest nutrient status of the soil of the experiment.

Parameters	Soil pH	Soil OM (%)	Available P (ppm)	Available K (ppm)
Pre-planting	6.00	3.29	41.95	1337.01
Post-Harvest:				
STR	5.91	3.18^{a}	41.84	1331.51^{a}
FPJ - subsurface	6.10	3.32^{b}	41.91	1341.53^{bcd}
FFJ - subsurface	6.00	3.32^{b}	41.97	1340.85^{bc}
FAA - subsurface	6.11	3.29^{ab}	41.89	1345.44^{d}
FE - subsurface	6.10	3.32^{b}	41.97	1338.97^{b}
FPJ - foliar	6.11	3.32^{b}	41.93	1343.81^{cd}
FFJ - foliar	6.10	3.32^{b}	41.94	1340.89^{bc}
FAA - foliar	6.11	3.31^{b}	41.96	1343.08^{bcd}
FE - foliar	6.00	3.32^{b}	41.91	1345.59^{d}
CV%	4.69	1.68	0.15	0.31

Column means of the same superscript are not statistically different at the 0.05 level. STR – soil test recommendation, FPJ – fermented plant juice, FFJ – fermented fruit juice, FAA – fish amino acid, FE – fermented eggshells, OM – organic matter, P – Phosphorus, K – Potassium, and ppm – parts per million

The effectiveness of foliar application supports broader research on organic-chelate fertilizers improving plant height compared to control treatments [30]. However, these results contrast with studies suggesting that surface application is as effective as incorporated amendments [31], particularly regarding FFJ treatments where application method significantly influenced outcomes. This divergence highlights the importance of considering specific amendment types and local conditions when selecting application methods. These findings have important implications for agricultural management, emphasizing the need for careful timing and environmental consideration in foliar applications [32]. The significant growth promotion achieved with FFJ-foliar treatment demonstrates the potential of fermented amendments as alternatives to conventional fertilizers, supporting the transition toward more sustainable agricultural practices [33]. Further research should focus on understanding nutrient uptake pathways and optimizing application timing to maximize treatment effectiveness [34].

3.2.2. Days to 50% flowering

Treatments demonstrated highly significant differences in flowering time ($p = 0.002$), with FFJ-subsurface promoting earliest flowering at 30.50 days while FE-subsurface delayed flowering until 57.55 days. The wide variation between treatments (30.50-57.55 days) indicates that both ferment type and application method substantially influence reproductive transition timing. This significant impact on developmental timing aligns with research showing nutrient elements as primary factors affecting plant developmental stages [27]. The effectiveness of subsurface versus foliar applications varied markedly by ferment type, with FFJ-subsurface showing superior performance in promoting early flowering. This accelerated flowering response can be attributed to efficient delivery of key nutrients and bioactive compounds to the root zone, supporting findings that subsurface application significantly improves nutrient uptake efficiency [9]. The mechanism involves beneficial microorganisms in fermented amendments solubilizing soil nutrients crucial for reproductive development [4]. FFJ-subsurface treatment's effectiveness in promoting early flowering stems from its unique characteristics and mode of action. Research has shown that fermented fruit extracts contain bioactive compounds that significantly improve physiological processes and plant development [35]. Conversely, the delayed flowering in FE-subsurface treatment reflects the gradual release and availability of nutrients from fermented eggshell applications [36]. Our findings support observations that organic fertilizers contribute to substantial improvements in plant developmental parameters [37], but they contrast with studies showing initially slower development under organic management [21]. This difference are results from variations in amendment types and application methods. These findings strongly support the study's objective of evaluating locally sourced bio-amendments and their application methods. The significant variation in flowering response demonstrates the potential for optimizing reproductive development through appropriate amendment selection and application method, aligning with goals for sustainable agricultural practices utilizing bio-based fertilizers [33]. Further research should focus on characterizing bioactive compounds and their pathways of action [5], as well as investigating nutrient interactions and their assimilation pathways to optimize treatment effectiveness [34].

3.2.3. Days to 50% fruiting

The study revealed highly significant differences in fruiting time among treatments ($p < 0.001$), with FFJ-subsurface treatment exhibiting the shortest period from flowering to fruiting at 0.97 days, while FE-foliar showed the longest period at 2.03 days. Other treatments demonstrated intermediate fruiting times ranging from 1.43 to 2.02 days (Table 2). This significant variation suggests that both the type of fermented bio-amendment and its application method substantially influence the reproductive development of okra. The notably faster fruiting response to FFJ-subsurface treatment indicates that fermented fruit juice, when applied below the soil surface, can optimize conditions for rapid fruit development. According to Sulok et al. [4], fermented fruit juices contain beneficial microorganisms capable of solubilizing soil nutrients, particularly phosphorus and potassium, which are crucial for reproductive development. The subsurface application enhanced nutrient availability in the root zone, as supported by Bhuiyan et al. [9], who found that subsurface nutrient placement significantly improved nutrient uptake efficiency. The slower fruiting response in FE-foliar treatment aligns with findings from Gulzar et al. [38], indicating that eggshell amendments primarily influence calcium availability rather than broader metabolic processes that might accelerate fruiting.

The study of Zhang et al. [35] demonstrated that fermented fruit extracts significantly improved physiological processes and development in fruit trees, supporting our observations of accelerated fruiting with FFJ treatments. The effectiveness of subsurface application is corroborated by Blackshaw et al. [39], who found that point-injected nutrients resulted in superior plant performance compared to surface applications. Additionally, Urra et al. [5] showed that fermented liquid organic amendments, when applied at optimal doses, could match or exceed the effectiveness of mineral fertilization in supporting crop development. The pronounced effect of FFJ-subsurface treatment on fruiting time has significant implications for agricultural management. As demonstrated by Fahrurrozi et al. [29], the effectiveness of soil application was 99.625% as effective as foliar application in influencing crop development, supporting our finding of superior performance with subsurface application. The rapid transition to fruiting observed with FFJ-subsurface treatment suggests potential benefits for reducing crop cycle duration and improving production efficiency. However, as noted by Derrick [32], successful implementation requires careful consideration of application timing and environmental conditions.

The fruiting response patterns show interesting correlations with flowering times, where FFJ-subsurface treatment consistently demonstrated accelerated reproductive development. This consistency across developmental stages suggests that the treatment's effects are sustained throughout the reproductive phase. The relationship between rapid fruiting and subsequent yield parameters is supported by Alzamel et al. [37], who found that organic fertilizer treatments contributed to substantial increases in production yield compared to inorganic treatments. Further investigation is needed to fully understand the mechanisms underlying the accelerated fruiting response to FFJ-subsurface treatment. As suggested by He et al. [27], nutrient elements are key factors affecting plant development, but the specific pathways and interactions need clarification.

Table 2. Growth of okra applied with various fermentation media blends by subsurface and foliar applications.

TREATMENT	Plant Height (cm)			No. of days flowering	No. of days fruiting
	30 DAS	60 DAS	90 DAS		
STR	11.56^{ab}	19.87^{ab}	59.07^{bc}	49.90^{ab}	1.83^{ab}
FPJ - subsurface	10.69^{a}	19.50^{ab}	51.15^{ab}	47.75^{ab}	1.43^{ab}
FFJ - subsurface	10.90^{a}	18.37^{a}	37.43^{a}	30.50^{a}	0.97^{a}
FAA - subsurface	12.43^{ab}	22.85^{b}	62.08^{bc}	54.45^{ab}	2.02^{b}
FE - subsurface	11.70^{ab}	23.30^{b}	59.43^{bc}	57.55^{b}	1.97^{b}
FPJ - foliar	11.58^{ab}	21.77^{ab}	55.00^{bc}	46.35^{ab}	1.67^{ab}
FFJ - foliar	12.63^{b}	23.83^{b}	62.32^{c}	53.15^{ab}	2.02^{b}
FAA - foliar	11.27^{ab}	22.82^{ab}	60.85^{bc}	50.87^{ab}	1.95^{b}
FE - foliar	11.90^{ab}	22.38^{ab}	55.90^{bc}	55.15^{b}	2.03^{b}
Chi-Square	16.026	21.01	47.176	24.3	30.294
Asymp. Sig.	0.042*	0.007*	<.001*	0.002*	<.001*

Column means of the same superscript are not statistically different at the .05 level Significant. Asymp. Sig. - Asymptotic significance, STR – soil test recommendation, FPJ – fermented plant juice, FFJ – fermented fruit juice, FAA – fish amino acid, FE – fermented eggshell

3.3. Yield traits

3.3.1. Fruit length and diameter

Fermentation media blends by subsurface and foliar applications showed significant differences in both fruit length ($p < 0.001$) and diameter ($p = 0.03$), with STR treatment producing the longest fruits (17.63 cm) and FFJ-foliar yielding the largest diameter (16.04 cm) in Table 3. The comparable performance between FFJ-foliar and STR treatments in fruit length, coupled with FFJ-foliar's superior performance in fruit diameter, demonstrates that bio-amendments can match or exceed conventional fertilization outcomes. This finding aligns with research showing that fermented organic amendments, when applied optimally, can produce results comparable to mineral fertilization [5]. The effectiveness of treatments varied notably by application method, with foliar applications showing superior results. FFJ-foliar's success in promoting fruit dimensions contrasts with the relatively lower performance of FAA-subsurface (14.81 cm length, 13.84 cm diameter), suggesting that nutrient composition and delivery method significantly influence fruit development [40]. The consistently better performance of foliar applications indicates that direct nutrient availability to developing fruits can be more efficient for size development, supporting research on the benefits of foliar nutrition for specific growth parameters [32].

Research indicates that organic amendments influence hormone balance and metabolic pathways crucial for fruit development [41]. The superior performance of FFJ-foliar treatment suggests efficient nutrient delivery and hormone regulation, aligning with findings that fermented fruit extracts can significantly improve physiological processes and fruit development [35]. This effectiveness relates to the importance of balanced nutrition for fruit development [42]. The comparable or superior performance of FFJ-foliar treatment to STR indicates its potential as a sustainable alternative to conventional fertilization, though success requires careful attention to application timing and method [43]. The results demonstrate that bio-amendments can maintain market-standard fruit dimensions while supporting sustainable agricultural practices [33]. Future research should focus on understanding nutrient uptake pathways and their influence on fruit development [34], with additional attention to optimizing application timing and concentration for improved treatment effectiveness.

3.3.2. Number of marketable and non-marketable fruits

Treatment effects showed highly significant differences in marketable fruit numbers ($p < 0.001$), with FAA-foliar producing the highest yield (3.00 fruits), followed by FFJ-foliar (2.57) and STR (2.15). The non-significant differences in non-marketable fruits ($p = 0.12$) suggest that treatments primarily influenced fruit quality development rather than defect reduction. Research shows that organic fertilizers can enhance product quality while maintaining low rejection rates [43], with foliar-applied organic fertilizers significantly improving crop productivity and quality parameters [30]. The superiority of foliar applications in marketable fruit production demonstrates application method's crucial role in treatment effectiveness. The marked contrast between foliar and subsurface applications, particularly evident in FFJ treatments (2.57 vs 0.83 marketable fruits), indicates that direct nutrient delivery through foliar application is more efficient for fruit quality development. This aligns with research on the benefits of foliar nutrition for specific quality parameters [32] and the timing-sensitive nature of foliar applications [28]. The exceptional performance of FAA-foliar treatment can be attributed to its unique compositional characteristics. Research shows that fish-based amendments provide readily available amino acids and nutrients that influence plant metabolism and fruit development [40]. Similarly, the effectiveness of FFJ-foliar treatment supports findings that fermented fruit extracts contain beneficial bioactive compounds [35]. The varying effectiveness among bio-amendments reflects different mechanisms through which organic amendments influence crop development [4].

Bio-amendments could effectively replace conventional fertilizers while maintaining or improving product quality [5], with foliar applications showing particularly high effectiveness in organic systems [29]. The success of locally sourced bio-amendments supports circular economy principles in agriculture [6], though management decisions should carefully consider application timing and method optimization [43]. Future research should focus on understanding the mechanisms behind FAA-foliar and FFJ-foliar treatments' superior performance in promoting marketable fruit development. Investigation of nutrient uptake pathways and their influence on fruit quality development, along with examination of the leaf-root-soil microbe conduction system, could provide valuable insights for optimizing treatment outcomes.

3.3.3. Weight of marketable and non-marketable fruits

Treatment effects revealed highly significant differences in marketable fruit weight ($p < 0.001$), with FFJ-foliar yielding the highest weight (72.50 g), followed by FAA-foliar (65.03 g) and STR (59.12 g). Non-marketable fruit weights showed near-significant differences ($p = 0.079$), ranging from 1.03 to 5.60 g. This pattern demonstrates that bio-amendments, particularly when foliar-applied, can exceed conventional fertilization in promoting fruit weight development, supporting research showing that organic fertilizers can enhance product quality and yield parameters while maintaining low waste production [43]. The marked difference between foliar and subsurface applications, particularly evident in FFJ treatments (72.50 g vs 29.40 g), indicates that application method significantly influences nutrient delivery and utilization. This aligns with research showing that fermented organic amendments can match or exceed mineral fertilization effectiveness [5], while the success of fish-based amendments supports findings about readily available nutrients in fish-based fertilizers [40].

Research indicates that organic amendments influence hormone balance and metabolic pathways crucial for fruit development [41], while foliar applications enable efficient nutrient translocation [32]. The source-sink relationships affecting fruit weight development support findings about the physiological effects of fermented amendments on fruit development [35]. These findings have significant economic and management implications for sustainable agriculture. The substantially higher marketable fruit weights achieved with FFJ-foliar and FAA-foliar treatments compared to STR demonstrate the potential for bio-amendments to enhance crop productivity [37]. However, successful implementation requires careful attention to application timing and method [43], with consideration of foliar nutrient influences on crop development [27]. Future research should focus on understanding the mechanisms behind foliar-applied bio-amendments' superior performance in promoting fruit weight. Investigation of nutrient uptake pathways and their influence on fruit development [34], along with optimization of application timing and concentration [5], could further improve treatment effectiveness.

Table 3. Yield characteristics of okra applied with various fermentation media blends by subsurface and foliar applications.

TREATMENT	Fruit Length	Fruit Diameter	No. Marketable Fruit	No. Non-marketable Fruit	Wt. Marketable Fruit	Wt. Non-marketable Fruit
STR	17.63^{b}	14.67^{ab}	2.15^{b}	0.37	59.12^{abc}	4.55^{bc}
FPJ - subsurface	15.29^{a}b	14.55^{ab}	1.17^{ab}	0.13	34.87^{ab}	1.03^{a}
FFJ - subsurface	15.40^{ab}	14.49^{ab}	0.83^{a}	0.17	29.40^{a}	1.67^{a}
FAA - subsurface	14.81^{a}	13.84^{a}	1.72^{b}	0.18	49.58^{abc}	2.97^{abc}
FE - subsurface	15.77^{ab}	14.44^{ab}	1.58^{b}	0.17	47.08^{abc}	2.10^{ab}
FPJ - foliar	14.96^{ab}	14.15^{ab}	1.38^{ab}	0.15	42.38^{abc}	2.13^{ab}
FFJ - foliar	17.39^{b}	16.04^{b}	2.57^{bc}	0.27	72.50^{c}	5.60^{c}
FAA - foliar	15.28^{ab}	14.64^{ab}	3.00^{c}	0.28	65.03^{c}	3.37^{bc}
FE - foliar	14.91^{ab}	13.92^{ab}	1.62^{ab}	0.2	46.27^{abc}	3.00^{abc}
Chi-Square	77.659	17.053	50.621	12.758	29.486	14.092
Asymp. Sig.	<.001*	0.03*	<.001*	0.12*	<.001*	0.079*

Column means of the same superscript are not statistically different at the .05 level Significant. Asymp. Sig. - Asymptotic significance, STR – soil test recommendation, FPJ – fermented plant juice, FFJ – fermented fruit juice, FAA – fish amino acid, FE – fermented eggshells

3.3.4. Nutrients of Okra fruits

Bio-amended treatments significantly influenced the nutritional composition of okra fruits, particularly affecting fiber content (Table 4). FAA-subsurface and FPJ-foliar treatments resulted in significantly lower fiber content (24.35%) compared to the STR treatment (24.46%), while maintaining consistent levels of ash (6.37-6.42%), protein (10.38-10.42%), and fats (1.38-1.41%). This reduction in fiber content suggests that fermented bio-amendments modulate plant metabolism differently than conventional fertilizer [44, 45]. The effectiveness of different ferment types varied notably based on their composition and application method. Fish Amino Acids demonstrated optimal performance when applied subsurface, aligning with research showing that fish-based ferments provide readily available amino acids that influence plant metabolism [40]. Similarly, plant-based ferments achieved comparable results through foliar application, supporting findings that fermented plant extracts can effectively influence plant development when properly delivered [46].

Application method played a crucial role in determining treatment effectiveness, with foliar applications generally resulting in lower fiber content compared to subsurface applications for the same ferment type. This pattern aligns with research demonstrating enhanced nutrient absorption through leaves [47] and the importance of direct nutrient access to plant metabolism [34]. The optimal performance of both FAA-subsurface and FPJ-foliar treatments suggests that specific ferment types work best with particular application methods. The variation in treatment effectiveness can be attributed to the complex composition and release patterns of bio-amendments. Research indicates that organic fertilizers affect biochemical parameters differently than chemical fertilizers due to their diverse nutrient profiles and gradual release characteristics [2, 48]. However, some contrasting findings exist, with certain studies reporting higher fiber content in organically grown vegetables [49], highlighting the importance of proper preparation methods and application timing in determining treatment outcomes [4]. These findings suggest that bio-amendments can effectively influence okra fruit quality parameters when properly formulated and applied. The success of specific ferment-application method combinations provides valuable insights for optimizing nutrient management systems in sustainable agriculture [10]. However, further research should focus on understanding the mechanisms behind these effects and optimizing application strategies for consistent results across different growing conditions.

Table 4. Effect of treatment on nutrient analysis of the okra fruits.

Sample	Ash (%)	Fiber (%)	Protein (%)	Fats (%)
STR	6.37	24.46^{d}	10.40	1.39
FPJ - subsurface	6.42	24.42^{cd}	10.41	1.40
FFJ - subsurface	6.42	24.43^{cd}	10.41	1.38
FAA - subsurface	6.40	24.35^{a}	10.38	1.40
FE - subsurface	6.40	24.44^{cd}	10.42	1.41
FPJ - foliar	6.38	24.35^{a}	10.40	1.38
FFJ - foliar	6.39	24.37^{ab}	10.41	1.39
FAA - foliar	6.41	24.40^{bc}	10.40	1.40
FE - foliar	6.40	24.37^{ab}	10.41	1.39
CV%	7.19	9.24	7.84	3.84

Column means of the same superscript are not statistically different at the .05 level. STR – soil test recommendation, FPJ – fermented plant juice, FFJ – fermented fruit juice, FAA – fish amino acid, FE – fermented eggshells

4. Conclusions

This study demonstrates that locally sourced fermented bio-amendments effectively influence okra growth, yield, and fruit quality, with outcomes varying significantly based on amendment type and application method. Bio-amendments maintained higher soil organic matter than conventional fertilization while sustaining stable pH levels and improving potassium availability, indicating their potential for sustainable soil management. Plant growth responses varied by treatment, with FFJ-foliar producing the tallest plants and FFJ-subsurface significantly accelerating flowering. Regarding fruit development, FFJ-foliar treatment achieved a maximum fruit diameter comparable to conventional fertilization. At the same time, FAA-foliar yielded the highest number of marketable fruits, and FFJ-foliar produced the highest marketable fruit weight. Additionally, bio-amendments resulted in lower fiber content compared to conventional treatment. Notably, the foliar application generally showed superior results to subsurface application, particularly for fruit quality parameters and marketable yield, though effectiveness varied by amendment type. These findings suggest that fermented bio-amendments, particularly FFJ and FAA applied through foliar methods, can be effective alternatives to conventional fertilization in okra production while supporting sustainable agricultural practices. However, successful implementation requires careful consideration of amendment type and application method to optimize results.

5. Declaration

5.1. Competing Interests

All authors declare no competing interest

5.2. Author Contributions

Author 1- designed the study, performed the statistical analysis and correspondence.

Author 2 -data gathering, managed the literature searched, and approved the final manuscript.

Author 3 - writing/drafting the manuscript, laboratory work/experimental procedures, and editing of the manuscript

5.3. Ethics Committee Approval

Not applicable

5.4. Acknowledgements

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