Sweet Pepper (*Capsicum annuum* L) Under Organic Nutrient Management - A Comparative Study of Agronomic and Economic Outcomes

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ABSTRACT

The transition to sustainable agriculture necessitates identifying fertilization strategies that are both ecologically sound and economically viable for farmers. This study provides a comprehensive evaluation of sweet pepper (*Capsicum annuum* L. 'Sultan F1') performance under various organic fertilization regimes compared to conventional inorganic fertilization and a no-fertilizer control. The experiment, conducted under the climatic stress of an El Niño season in Maguindanao, Philippines, was laid out in a Randomized Complete Block Design with ten treatments, including Korean Natural Farming (KNF) concoctions, vermicompost-based applications, and their combinations. Results demonstrated that all organic treatments significantly improved plant growth, yield, and postharvest quality over the control. The combination of KNF and vermi-based fertilizers produced the highest marketable yield (9,700 kg/ha), nearly meeting industry standards and suggesting that integrated organic systems can effectively bridge the yield gap. Critically, all organic treatments significantly enhanced postharvest performance, extending storage life and reducing weight loss by up to 16% compared to the inorganic treatment. From an economic standpoint, the KNF-only treatment, utilizing low-cost, on-farm inputs, yielded an exceptional Return on Investment (ROI) of 192%, far surpassing the inorganic fertilizer treatment (113%) and all other organic combinations. This highlights a crucial distinction between maximizing yield and maximizing profitability. These findings provide robust empirical evidence that low-cost organic systems like KNF are not only agronomically effective, particularly in enhancing postharvest quality, but also represent a highly profitable and accessible pathway for smallholder farmers to achieve sustainable and resilient crop production.

Keywords: *Capsicum annuum*, organic fertilizer, Korean Natural Farming (KNF), vermicompost, postharvest quality, economic viability, sustainable agriculture

INTRODUCTION

Sweet pepper (*Capsicum annuum* L.), a member of the Solanaceae family, is a globally significant vegetable crop valued for its culinary versatility and rich nutritional profile, containing high levels of vitamins A, C, and E, as well as over 30 different carotenoids (Bosland et al., 2012; Akbar et al., 2022; Muscolo et al., 2022). Global production of chillies and peppers reached over 36 million tons in 2021, with market projections indicating a continued upward trend in demand through 2025 (FAO, 2021; Hakim et al., 2021). Despite its global importance, production is often hampered by regional deficits and agronomic challenges.

In the Philippines, particularly in the southern region of Mindanao, a significant gap exists between supply and demand. A 2012 report highlighted a weekly shortage of 73 metric tons for sweet and bell peppers, with the former Autonomous Region in Muslim Mindanao (ARMM) contributing only 4% of the regional supply, the lowest of all region. This underscores a critical need for research and extension programs focused on enhancing production, adaptability, and postharvest handling within the region. a municipality within this region, has suitable climatic conditions for vegetable cultivation but records an average sweet pepper yield of only 3.22 tons per hectare, far below the national industry standard of 10 to 15 tons per hectare. This production gap is exacerbated by challenges farmers face in adopting effective fertilization practices and managing pests and diseases, which hinder both the volume and quality of the produce.

In response to the environmental and health concerns associated with conventional agriculture, which relies heavily on synthetic chemical inputs, organic farming has emerged as a promising alternative (Clark &Tilman, 2017; Schrama et al., 2018). Organic agriculture is a holistic production management system that promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity (Zuccaro et al., 2024). It is founded on the principles of minimizing external inputs, avoiding synthetic fertilizers and pesticides, and fostering ecological balance to achieve sustainable production (Clark & Tilman, 2017; Zuccaro et al., 2024). For high-value crops like sweet pepper, which are often listed among produce with high pesticide residues when grown conventionally, organic methods offer a pathway to producing safer, healthier food.

However, a primary challenge for farmers considering a transition to organic methods is the ability to achieve yields, product quality, and financial returns that are comparable to those of conventional systems (Catalan, 2019). This concern is particularly acute for smallholder farmers in developing countries, who require production systems that are not only sustainable but also economically viable and resilient to climate-related stressors (UNCTAD, 2006; Badgley et al., 2007). This study was conceptualized to address this challenge directly by evaluating various organic fertilization strategies to identify those that can enhance sweet pepper productivity and profitability for farmers in the southern Philippines.

Recent research has significantly advanced the understanding of organic fertilization's impact on *Capsicum* species, focusing on soil health, nutrient delivery, crop performance, and product quality.

Vermicompost, an organic amendment produced through the digestion of organic waste by earthworms, has been consistently shown to be a potent fertilizer for sweet pepper. Recent studies confirm that its application enhances soil structure, nutrient availability, and microbial activity, leading to significant improvements in plant growth parameters such as height, leaf area, and biomass (Zaki et al., 2023; Alaboz & Ortas, 2024; Al-Ali et al., 2023; Yadav et al., 2024). The co-application of vermicompost with biochar has demonstrated synergistic effects, further improving agro-physiological properties, enhancing the nutritional quality of fruits, and notably reducing fruit nitrate concentrations, a key indicator of food safety (Al-Ali et al., 2023; Lacomino et al., 2020).

The frontier of organic fertilization is increasingly focused on the use of biostimulants and microbial inoculants. These products, which include beneficial microorganisms known as Plant Growth Promoting Microorganisms (PGPMs), seaweed extracts, and other biological preparations, enhance nutrient use efficiency, tolerance to abiotic stress, and overall crop quality (Reis et al., 2024; Baker et al., 2020; Celiktopuz et al., 2020; Jiménez-Arias et al., 2021; Lau et al., 2022). For instance, a recent study demonstrated that Carrageenan Plant Growth Promoter (CPGP), a foliar biostimulant, significantly accelerated maturation and increased the number and weight of fruits in pepper (Hakim et al., 2021). Similarly, foliar application of organic acids and other biological treatments has been shown to be an effective method for rapid nutrient delivery, bypassing soil-related nutrient lock-up and boosting plant development and resistance to stress (Muscolo et al., 2022). These findings underscore a shift towards precision nutrient management in organic systems, where targeted biological inputs complement soil-building practices.

Korean Natural Farming (KNF) is a holistic agricultural system that emphasizes the use of on-farm, low-cost inputs derived from natural materials. Its core practices involve the cultivation and application of indigenous microorganisms (IMOs) to enhance soil life and the use of fermented plant extracts—such as Fermented Plant Juice (FPJ) and Fermented Fruit Juice (FFJ)—as foliar feeds and biostimulants (Cho, n.d.). The philosophy of KNF aligns with regenerative agriculture, aiming to create a self-sustaining, closed-loop system that minimizes external inputs and builds soil health (Fukuoka, 2009).

Despite strong anecdotal support from practitioners and a growing global community, KNF remains scientifically under-validated (Garden Myths, n.d.). A review of literature from 2020-2024 reveals a significant scarcity of rigorous, peer-reviewed studies that quantitatively assess the agronomic, postharvest, and economic performance of KNF compared to other organic and conventional systems (KNF Hawaii, n.d.; Wang et al., n.d.; Lee, n.d.; ECHO Community, n.d.). While the theoretical underpinnings of its components are sound—research confirms that fermented plant extracts are rich sources of bioactive compounds with antioxidant and antimicrobial properties (Various authors, 2024; Wang et al., 2024)—there is a clear evidence gap regarding

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the performance of the KNF system as a whole in controlled field experiments. This lack of scientific validation presents a barrier to its wider adoption and integration into mainstream agricultural recommendations.

The persistent sweet pepper supply deficit in the southern Philippines, coupled with the global imperative for sustainable agricultural practices, creates a strong impetus for research into effective and accessible organic production systems. This study addresses this need by providing a comprehensive, multi-faceted evaluation of various organic fertilization strategies, including established methods like vermicomposting and the promising but under-researched KNF system.

Presenting robust empirical data on agronomic performance, postharvest quality, and, most critically, economic profitability, this research aims to fill the identified scientific evidence gap surrounding KNF. It provides a valuable case study conducted under the real-world stress of an El Niño season, testing the resilience and efficacy of these organic systems. Therefore, the objectives of this study were:

1. To determine the effects of different organic fertilizers—including KNF, vermicompost, and their combinations—on the growth, yield, and postharvest performance of sweet pepper.
2. To compare the performance of these organic treatments against each other and against conventional inorganic fertilization and a no-fertilizer control.
3. To evaluate the financial profitability and return on investment of each fertilization regime, thereby assessing their economic viability for smallholder farmers.

METHODS

The field experiment was conducted at Maguindanao, Philippines (*7° 01'34.76" N, 124° 09'55.87" E*), at an elevation of 447.14 meters above sea level. The study period coincided with a mid-season El Niño event, characterized by low rainfall (average 0.355 mm daily) and high average daily temperatures (29.9 °C), creating conditions of significant abiotic stress for the crop.

The experiment was laid out in a Randomized Complete Block Design (RCBD) with four replications (Figure 1). The study consisted of ten distinct fertilizer treatments, detailed in Table 1, which included a no-fertilizer control, a conventional inorganic fertilizer regime, and eight different organic fertilization strategies based on Korean Natural Farming (KNF), vermicompost, and their various combinations. Each experimental plot measured 1 x 5 m, with ten sample plants per treatment used for data collection.

Figure 1 – Randomized Complete Block Design with Four Replications Used in the Study.

Buffer area 4m wide	Buffer area 4m wide							Buffer area 4m wide
	R1 (Block)	Distance (D) between Blocks - 3 m	R2 (Block)	Distance (D) between Blocks - 3 m	R3 (Block)	Distance (D) between Blocks - 3 m	R4 (Block)	
	T10		T3		T5		T8	
	T2		T5		T6		T7	
	T5		T4		T9		T3	
	T4		T6		T1		T5	
	T8		T8		T3		T1	
	T7		T9		T10		T9	
	T1		T2		T2		T6	
	T3		T10		T7		T4	
	T9		T1		T8		T2	
	T6		T7		T4		T10	
	Buffer area 4m wide							

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Table 1. Description of Experimental Treatments Applied to Sweet Pepper (*Capsicum annuum* L.)

Treatment Code	**Description**	**Basal Application (Rate)**	**Foliar/Side-Dress Application (Rate and Frequency)**
T1	Control	None	None
T2	Inorganic Fertilizers	5 g/m² Complete (14-14-14)	5 g/m² Urea (46-0-0) side-dressed once at 20 DAT
T3	KNF Organic Fertilizers	None	20 mL/L of FPJ, FFJ, FAA, LABS, and IMO applied as a foliar spray every 14 days
T4	Vermi-based Organic Fertilizers	2 kg/m² Vermicompost	500-1000 mL Vermitea / 16 L water applied as a foliar spray every 14 days
T5	Combined KNF + Vermi-based	2 kg/m² Vermicompost	20 mL/L of FPJ, FFJ, FAA, LABS, and IMO + Vermitea applied as a foliar spray every 14 days
T6	Vermicompost + IMO	2 kg/m² Vermicompost	20 mL/L IMO applied as a foliar spray every 14 days
T7	Vermicompost + LABS	2 kg/m² Vermicompost	20 mL/L LABS applied as a foliar spray every 14 days
T8	Vermicompost + FAA	2 kg/m² Vermicompost	20 mL/L FAA applied as a foliar spray every 14 days
T9	Vermicompost + FFJ	2 kg/m² Vermicompost	20 mL/L FFJ applied as a foliar spray every 14 days
T10	Vermicompost + FPJ	2 kg/m² Vermicompost	20 mL/L FPJ applied as a foliar spray every 14 days

Note: DAT = Days After Transplanting; KNF = Korean Natural Farming; IMO = Indigenous Microorganisms; LABS = Lactic Acid Bacteria Serum; FAA = Fish Amino Acid; FFJ = Fermented Fruit Juice; FPJ = Fermented Plant Juice.

Preparation and Application of Fertilizer Treatments

Prior to the experiment, the field was conditioned by planting mung bean (*Vigna radiata* L.) as a green manure crop, which was plowed back into the soil to enhance microbiological homogeneity and fertility. The organic inputs were prepared according to standard KNF protocols. Fermented Plant Juice (FPJ) was made from water spinach (*Ipomoea aquatica*) and kakawate leaves (*Gliricidia sepium*); Fermented Fruit Juice (FFJ) from papaya (*Carica papaya*); Fish Amino Acid (FAA) from raw fish; Lactic Acid Bacteria Serum (LABS) from rice wash and milk; and Indigenous Microorganisms (IMO) were cultured from local forest soil using cooked rice as a substrate. Vermicompost and vermitea were sourced from a local producer. All treatments were applied according to the rates and frequencies specified in Table 1.

Crop Management and Data Collection Protocols

Healthy, hardened seedlings of sweet pepper 'Sultan F1' were transplanted at 30-35 days old, with a planting distance of 50 x 50 cm. Standard cultural management practices, including manual weeding and irrigation, were uniformly applied across all treatments. Irrigation was scheduled based on soil moisture monitoring. For pest management in the organic treatments, Oriental Herb Nutrient (OHN), a KNF preparation, was used as a repellent.

Data on growth and yield parameters were collected from the ten sample plants per plot. Growth parameters included plant height (cm), number of leaves, specific leaf area (cm²), and plant canopy area (cm²). Leaf and canopy area were measured non-destructively using the Easy Leaf Area mobile application (Easlon & Bloom, 2014). Reproductive parameters included days to first flowering and days to first fruit ripening. Yield parameters, collected over four harvestings up to 80 days after transplanting (DAT), included the number of fruits per plant, average fruit weight (g), and marketable and non-marketable yield (kg/ha).

Postharvest Quality and Economic Assessment

For postharvest analysis, ten fruits of uniform size and maturity (mature green to breaker stage) were harvested from each treatment. The fruits were washed, air-dried, and stored at ambient room temperature (approx. 24 °C) for evaluation. Postharvest quality was assessed daily by monitoring: 1) Visual Quality Rating (VQR) on a scale of 1 (non-edible) to 9 (excellent, field-fresh); 2) Visual Color Rating (VCR) to track ripening progression; 3) cumulative percentage weight loss, calculated from daily weight measurements; and 4) storage life, defined as the number of days until the fruit reached the limit of edibility (VQR ≤ 3).

A cost and return analysis was conducted to evaluate the economic viability of each treatment. All production expenses, including materials and labor, were recorded. The projected gross income was calculated based on the marketable yield and a standard farmgate price. From these figures, the net income and the Return on Investment (ROI) were computed for each treatment on a per-hectare basis. All collected data were subjected to Analysis of Variance (ANOVA), and treatment means were compared using Tukey's Honest Significant Difference (HSD) test at a 5% level of significance.

RESULTS

Influence of Organic Fertilizers on Vegetative and Reproductive Growth

The application of different organic and inorganic fertilizers had a significant effect on the growth parameters of sweet pepper (Table 2). Plant height was greatest in treatments T3 (KNF), T4 (Vermi-based), and T2 (Inorganic), which were statistically comparable to each other and significantly taller than all other treatments. The control plants (T1) were the shortest. In terms of leaf production, T2 (Inorganic) produced the highest number of leaves (92.5), which was significantly more than all organic treatments. Among the organic treatments, T3 (KNF), T4 (Vermi-based), and several vermicompost combinations (T8, T9, T10) performed well, producing between 82 and 85 leaves per plant.

The number of days to first flowering was earliest in T3 (KNF) and T6 (Vermi+IMO), which flowered at approximately 21 days, similar to the control (T1) and significantly earlier than the inorganic treatment (T2) at 23 days. Conversely, fruit ripening was delayed in the highest-performing treatments. Fruits from T2 (Inorganic), T3 (KNF), and T4 (Vermi-based) took the longest to ripen (59-60 days), whereas fruits from the control and treatments with lower nutrient inputs like T9 (Vermi+FFJ) and T10 (Vermi+FPJ) ripened earliest at around 53 days.

Comparative Analysis of Yield and Fruit Characteristics

Yield and its components were significantly influenced by the fertilization regimes (Table 2). The highest marketable yield was recorded in T5 (Combined KNF + Vermi-based) at 9,700 kg/ha. While this was the top-performing treatment, the yields of T4 (Vermi-based) at 5,942 kg/ha and T3 (KNF) at 5,639 kg/ha were also substantial, though statistically lower than T5. The inorganic treatment (T2) produced a marketable yield of 4,651 kg/ha, which was comparable to several of the vermicompost-combination treatments but significantly lower than the top three organic strategies.

Average fruit weight was maximized in the primary organic treatments, with T5, T4, and T3 producing the heaviest fruits (39-40 g), significantly heavier than those from the inorganic treatment (32.2 g) and the control (22.1 g). A critical indicator of fruit quality and crop health, the proportion of non-marketable fruits, revealed a distinct advantage for organic methods. The T2 (Inorganic) treatment produced the highest amount of non-marketable yield. In contrast, the T3 (KNF) treatment produced the lowest percentage of non-marketable fruits, indicating better overall plant health and fruit quality under this regime.

Table 2. Summary of Effects on Sweet Pepper Growth and Yield Parameters

Treatment	Plant Height (cm)	Marketable Yield (kg/ha)	Avg. Fruit Weight (g)	Non-Marketable Fruits (%)
T1 - Control	29.9 a	2,772 a	22.1 a	29.4 d
T2 - Inorganic	52.7 e	4,651 c	32.2 c	34.6 e
T3 – KNF	53.8 e	5,639 d	39.1 d	13.3 a
T4 - Vermi-based	53.2 e	5,942 d	39.4 d	16.4 b
T5 - Combined KNF+Vermi	46.6 d	9,700 e	40.0 d	13.0 a
T6 - Vermi+IMO	43.0 bc	4,227 c	32.0 c	22.0 c
T7 - Vermi+LABS	41.7 b	3,755 b	32.2 c	30.0 d
T8 - Vermi+FAA	41.5 b	4,683 c	32.8 c	25.5 d
T9 - Vermi+FFJ	44.1 c	3,825 b	30.6 b	26.3 d
T10 - Vermi+FPJ	43.6 c	3,806 b	32.3 c	26.4 d
Means in the same column followed by the same letter are not significantly different at p<0.05 by Tukey's HSD. Non-marketable fruit percentage calculated from marketable and non-marketable yield data.				

Postharvest Performance and Shelf-Life

The postharvest evaluation revealed significant advantages for all organic treatments over the inorganic control (Table 3). The storage life of fruits from the inorganic treatment (T2) was the shortest, reaching the limit of edibility (VQR ≤ 3) in just 7 days. In stark contrast, fruits from all organic treatments exhibited significantly longer shelf-life. Notably, fruits from T3 (KNF) and T1 (Control) remained edible for up to 16 days, more than doubling the storage period of the inorganic fruits.

This extended shelf-life was strongly correlated with reduced water loss during storage. Fruits from the T2 (Inorganic) treatment suffered the highest cumulative weight loss, losing 33.6% of their initial weight. All organic treatments demonstrated superior water retention. The lowest weight loss was observed in T5 (Combined KNF+Vermi) and T3 (KNF), both at approximately 17%, followed closely by T7 (Vermi+LAS) at 18%. The other organic treatments all maintained weight loss between 20-23%, which was still significantly better than the inorganic treatment. In terms of color development, there were no significant differences among treatments; all harvested fruits progressed from mature green to fully ripe red within approximately 6 days of storage.

Table 3. Summary of Effects on Sweet Pepper Postharvest Quality

Treatment	Storage Life (days until VQR ≤ 3)	Total Weight Loss (%)
T1 – Control	16 d	27.0 d
T2 – Inorganic	7 e	33.6 e
T3 – KNF	16 d	17.0 a
T4 - Vermi-based	13 c	22.0 bc
T5 - Combined KNF+Vermi	13 c	17.0 a
T6 - Vermi+IMO	13 c	20.0 abc
T7 - Vermi+LABS	13 c	18.0 ab
T8 - Vermi+FAA	13 c	23.0 cd
T9 - Vermi+FFJ	13 c	21.0 abc
T10 - Vermi+FPJ	13 c	22.0 bc
Means in the same column followed by the same letter are not significantly different at p<0.05 by Tukey's HSD. Storage life estimated from VQR data.		

Economic Performance and Return on Investment

The cost and return analysis translated the agronomic results into a clear assessment of economic viability for farmers (Table 4). The analysis revealed a dramatic divergence between yield performance and profitability. While T5 (Combined KNF+Vermi) generated the highest gross income due to its superior yield, its high

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production expenses (Php 157,060/ha), driven by the cost of both vermicompost and KNF inputs, resulted in a strong but not leading ROI of 147%.

The most striking economic result was from T3 (KNF). Despite having a moderate yield, its extremely low production cost (Php 77,300/ha), which was the lowest among all fertilized treatments, led to an outstanding ROI of 192%. This performance significantly outstripped that of the T2 (Inorganic) treatment, which had an ROI of 113%. The high cost of commercially produced vermicompost was a major financial constraint, leading to low or even negative ROIs for treatments that relied heavily on it without a corresponding high yield, such as T7 (Vermi+LAS) and T10 (Vermi+FPJ).

Table 4. Cost and Return Analysis of Sweet Pepper Production per Hectare

Treatment	Total Expenses (Php)	Gross Income (Php)	Net Income (Php)	Return on Investment (ROI, %)
T1 - Control	84,400	110,872	26,472	31
T2 - Inorganic	87,200	186,031	98,831	113
T3 – KNF	77,300	225,564	148,264	192
T4 - Vermi-based	153,580	237,682	84,102	55
T5 - Combined KNF+Vermi	157,060	388,000	230,940	147
T6 - Vermi+IMO	153,340	169,060	15,720	10
T7 - Vermi+LABS	153,880	150,199	(3,681)	-2
T8 - Vermi+FAA	153,880	187,323	33,443	22
T9 - Vermi+FFJ	153,760	153,001	(759)	0
T10 - Vermi+FPJ	153,340	152,237	(1,103)	-1
All values are in Philippine Pesos (Php) and calculated on a per-hectare basis. Farmgate price was assumed at Php 40/kg.				

Organic Amendments and Plant Growth: Corroboration and Contrasts with Recent Findings

The findings that vermicompost-based treatments (T4-T10) significantly improved plant growth parameters compared to the unfertilized control align strongly with a large body of contemporary research. Recent studies consistently demonstrate that vermicompost enhances the growth, yield, and quality of sweet pepper by improving soil physicochemical properties, increasing nutrient availability (N, P, K), and stimulating beneficial microbial communities (Zaki et al., 2023; Alaboz & Ortas, 2024; Al-Ali et al., 2023; Yadav et al., 2024). The observed increases in plant height and fruit weight in the vermicompost treatments can be attributed to the slow release of essential nutrients and the presence of plant growth-promoting substances like humic acids, which are known to be abundant in high-quality vermicompost (Al-Ali et al., 2023).

The observation that the inorganic fertilizer treatment (T2) produced the highest number of leaves and the largest canopy area is also consistent with established plant physiology . The rapid availability of synthetic nitrogen promotes vigorous vegetative growth. However, this study, along with others, suggests that this accelerated biomass accumulation does not necessarily translate into superior yield quality or resilience. For instance, excessive nitrogen application has been linked to increased plant susceptibility to pests and diseases and can negatively impact the concentration of secondary metabolites responsible for flavor and health benefits (Akbar et al., 2022; Muscolo et al., 2022). This trade-off is evident in the higher incidence of non-marketable fruits and poor postharvest performance of the inorganic treatment in this study.

Bridging the Yield Gap: The Efficacy of KNF and Vermicompost Combinations

A central debate in organic agriculture is its ability to match the yields of conventional systems. This study offers compelling evidence that integrated organic approaches can effectively bridge this yield gap. The combined KNF and vermi-based treatment (T5) produced the highest marketable yield (9,700 kg/ha), a figure that approaches the lower end of the industry standard (10,000 kg/ha) and significantly surpassed the yield of the conventional treatment (4,651 kg/ha).

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This superior performance likely stems from a synergistic interaction between the two organic components. Vermicompost provides a stable, long-term foundation of soil health, improving soil structure, water retention, and a slow-release nutrient pool (Al-Ali et al., 2023). This foundation is then supplemented by the KNF inputs, which act as potent biostimulants. The foliar application of fermented juices (FPJ, FFJ) and microbial inoculants (IMO, LABS) provides a rapid infusion of readily available nutrients, enzymes, and beneficial microorganisms directly to the plant at critical growth stages (Muscolo et al., 2022; Reis et al., 2024; Muscolo et al., 2022). This dual strategy of building soil health from the ground up while providing targeted, plant-available nutrition via foliar feeds represents a sophisticated organic management system that mirrors the principles of modern biostimulant research (Hakim et al., 2021; Reis et al., 2024). The success of this combined approach under the drought and heat stress of El Niño further suggests that the enhanced soil organic matter from vermicompost improved the plants' water-use efficiency and overall resilience.

Enhancing Postharvest Longevity and Quality through Organic Practices

One of the most significant findings of this study is the dramatic improvement in postharvest quality and shelf-life of organically grown sweet peppers. Fruits from all organic treatments demonstrated significantly lower weight loss and lasted substantially longer in storage than those from the inorganic treatment. This is not merely a side effect but a key performance indicator of a healthier, more resilient plant system.

Recent postharvest science provides a clear mechanism for these observations. Organic farming practices, which foster complex soil-plant-microbe interactions, often lead to the production of fruits with higher concentrations of secondary metabolites, such as phenolics and antioxidants (Muscolo et al., 2022; Mouratiadou et al., 2024). These compounds not only contribute to the nutritional value but also play a crucial role in the plant's natural defense system against pathogens and environmental stress, which translates to better post-storage resilience (Various authors, 2024). Furthermore, balanced, slow-release nutrition from organic sources tends to promote the development of stronger cell walls and dermal systems, making the fruit less susceptible to physiological water loss and microbial decay (Zaki et al., 2023; Mahmoud et al., 2020; Zaidi et al., 2024; Arah et al., 2015). The lower incidence of non-marketable fruits in the field for the KNF treatment (T3) provides in-season evidence of this enhanced plant health, which logically extends to the postharvest phase. The poor storage performance of the inorganically grown peppers, conversely, can be attributed to rapid, forced growth leading to weaker cellular structures that are more prone to rapid deterioration.

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This extended shelf-life is not just an agronomic curiosity; it translates directly into significant market advantages and economic benefits, particularly for smallholder farmers. Postharvest losses for perishable crops like sweet pepper can be as high as 40% globally, with the economic burden often falling on farmers through reduced prices and on consumers through increased costs. By extending the freshness of the produce, the organic methods demonstrated in this study directly combat these losses. A longer shelf-life enables farmers to access more distant markets, reduces the risk of shipment rejections, and allows for more flexibility in storage and distribution, which can lead to better and more stable pricing. For smallholders, reducing postharvest loss is a direct path to increased income, improved food security for their families and communities, and greater overall economic resilience. The World Bank estimates that even a 1% reduction in postharvest losses can yield tens of millions of dollars in economic gains, a significant portion of which benefits smallholder farmers directly. Therefore, the enhanced postharvest quality observed in the organic treatments represents a critical, tangible benefit that enhances the market viability and profitability of sustainable farming practices.

The Economic Case for Low-Cost Organic Systems - Validating the Profitability of KNF for Smallholders

The economic analysis presents arguably the most impactful conclusion of this study, highlighting a critical distinction between maximizing yield and maximizing profit. The standout result is the 192% Return on Investment (ROI) for the KNF-only treatment (T3), a figure that dramatically surpasses the inorganic treatment (113%) and even the highest-yielding organic treatment (T5 at 147%) .

This directly addresses a major barrier to organic adoption for smallholders in developing countries: the high cost of certified organic inputs and the perception of increased labor (UNCTAD, 2006; The Organic Center, 2020; Grovermann, 2023). Recent economic analyses of organic farming in the Philippines confirm its general profitability, largely driven by price premiums, but also acknowledge the challenges of input costs (Javier & Sison, 2023; INNSPUB, 2023). This study provides a powerful case study of a solution. The remarkable profitability of the KNF system is driven by its reliance on inputs that are produced on-farm using locally available, often free, materials (e.g., forest soil, plant trimmings, rice wash) . This drastically reduces cash outlay, making the system highly accessible to resource-limited farmers.

The trade-off between the highest-yielding treatment (T5) and the most profitable (T3) is instructive. The addition of purchased vermicompost to the KNF system in T5 nearly doubled the production expenses (from Php 77,300 to Php 157,060 per hectare) for a yield increase that, while substantial, did not provide a proportional increase in net income . For a smallholder farmer, managing input costs and financial risk is often a higher priority than achieving maximum absolute yield. This study demonstrates that a well-managed, low-cost organic system like KNF can provide a more economically rational and resilient path to profitability.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While the findings of this study are robust within its experimental context, certain limitations must be acknowledged. The data were collected from a single cropping season at a single location, and the performance of these systems could vary under different climatic conditions, soil types, and pest pressures.

Therefore, these results lay the groundwork for critical future research. There is a pressing need for:

1. **Long-term studies -** Multi-season, multi-location trials are needed to validate the residual effects of these organic treatments on soil health, nutrient cycling, and long-term productivity.
2. **Scientific validation of KNF inputs -** The mechanisms behind KNF's success remain a "black box." Research should focus on the microbiological characterization of IMO cultures and the chemical and nutritional analysis of fermented extracts like FPJ and FAA to move from anecdotal practice to scientific understanding.
3. **Expanded economic analysis -** The exceptional ROI of KNF found in this study should be replicated across different crops and regions to confirm its broad applicability as an economic model for smallholder organic agriculture.
4. **Integrated pest and disease management -** Future studies should investigate the specific plant defense mechanisms that may be induced by KNF applications, which could explain the observed reduction in non-marketable fruits.

This study provides compelling evidence that organic fertilization strategies can significantly enhance the agronomic performance, postharvest quality, and economic profitability of sweet pepper production, even under challenging climatic conditions. The findings demonstrate that integrated organic systems, such as the combination of Korean Natural Farming and vermicompost, are capable of achieving high yields that can bridge the gap with conventional industry standards.

More importantly, the research highlights that a focus on low-cost, on-farm inputs is the key to unlocking the economic potential of organic agriculture for smallholder farmers. The Korean Natural Farming (KNF) system, with its exceptional 192% Return on Investment, stands out as a highly accessible and profitable model. It proves that maximizing profitability does not always require maximizing yield, but rather optimizing the balance between production costs and outputs. The superior postharvest life and quality of all organically grown fruits further add to their market value and reduce post-production losses.

Ultimately, this research validates the hypothesis that organic agriculture, particularly through systems like KNF, offers a viable and empowering pathway for farmers in regions like the Philippines. It moves beyond a simple comparison of organic versus conventional, offering a nuanced analysis of different organic strategies and providing a clear, data-driven recommendation for a practice that is simultaneously sustainable, resilient, and profoundly profitable. These findings should inform agricultural policy and extension services to promote the adoption of such low-cost, high-return organic systems, thereby supporting the livelihoods of smallholder farmers and advancing the goal of a more sustainable food future.

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