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Research article

Integrating vermicompost, black soldier fly, and inorganic fertilizers enhances corn growth and yield

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ABSTRACT

To achieve good agricultural practices and maximize the economic yield of corn, farmers should reduce the use of inorganic fertilizers. A field experiment was conducted in the Chonnabot district, Khon Kaen province, Thailand, during the 2022 and 2023 growing seasons. The aim was to assess the impact of different organic fertilizers and their combinations on the growth and yield of commercial sweet corn (*Zea mays* L. saccharata) and waxy corn (*Zea mays* L. var. ceratina) hybrids. The results showed that sweet corn had significantly higher ear fresh weight, protein, fat, and fiber content compared to waxy corn, with values of 7,529.20 kg ha^{-1}, 14.48 %, 4.74 %, and 1.30 %, respectively. Two treatments, F4 (190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}) and F3 (6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}) resulted in the highest ear fresh weight, with 6,569.90 and 6,275.40 kg ha^{-1}, respectively. In contrast, F4 showed higher protein (12.04 %), fat (4.62 %), and fiber content (0.91 %) than F3. Significant improvements were observed in SPAD value, biomass, and yield parameters. Corn plants treated with a combination of vermicompost, BSF, and inorganic fertilizer showed higher ear length, ear diameter, ear fresh weight, and dry biomass than control plants (no fertilizer management, F1). The F1 treatment led to higher carbohydrate content in both corn cultivars tested, with a notable impact on pink waxy corn (82.06 %). Our findings suggest that using a combination of BSF and inorganic fertilizers is promising for reducing the use of inorganic fertilizers and providing the highest net income among the three fresh corn cultivars. Pink waxy corn showed greater adaptability under low soil fertility conditions owing to better yield components than purple waxy corn when evaluated without fertilizers.

1. Introduction

Fresh corn (*Zea mays* L.) is a significant cereal for human consumption and food production. It contains a type of protein called prolamine, which is abundant in cereal seeds, including wheat, sorghum, rice and barley [1]. There are different varieties of corn, including sweet corn, which is rich in sugar, and waxy corn, which contains various health-promoting compounds. After harvesting the economic yield at the milking stage, the by-products of fresh corn, such as leaves and stems, are used as animal feed. Corn is also a major source of oil, gluten, and starch, which can be hydrolyzed and enzymatically treated to produce syrups, particularly high-fructose corn syrup [2]. Waxy and sweet corns are grown in various regions of the world. China is one of the largest producers of waxy corn, which is also grown in South Korea, Japan, and the United States. The United States is the world's largest producer of sweet

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corn, followed by China, Mexico, Thailand, Brazil, the European Union, and India [3]. In Thailand, waxy and sweet corn are commonly grown by farmers due to their faster harvest and ability to generate extra income.

Inorganic fertilizers can provide immediate nutrients to crops, increasing yields in the short term. However, their overuse can create imbalances in the soil, leading to long-term problems. Excessive application of chemical fertilizers can degrade soil health, affecting productivity and sustainability [4]. Farmers may also incur significant costs if the market prices for crops do not offset input expenses. Today, consumers prefer foods with medicinal properties, and corn is an important cereal crop used in various food products. Proper fertilizer management is crucial for maximizing yields, reducing environmental impact, and ensuring crop growth [5]. Good Agricultural Practices (GAP) are a set of standards for the safe and sustainable production of crops and livestock. By integrating inorganic fertilizers with organic phosphate, we can take the first step towards decreasing the use of inorganic fertilizers without adversely impacting the economic yield. In addition, crop production under GAP standards is an alternative strategy that can increase sustainable and commercially viable agricultural production, as well as improve soil biodiversity and health [6,7].

Vermicompost and black soldier fly (BSF) are organic fertilizers that contain complete nutrients, including phosphate, and are alternatives to reduce the detrimental effects of inorganic materials [8]. Vermicompost is a well-decomposed organic matter produced by interactions between microorganisms and earthworms. It contains macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), and growth-stimulating hormones, and has high water-holding capacity, porosity, soil conservation tendency, and microbial activity [9,10]. Meanwhile, BSF contains 41.2 % N, 32.4 % P, and 77.1 % K of NPK content [11], and is recognized for maintaining the availability of N in the soil for crop growth, such as corn [12,13]. The use of insect frass fertilizers, like BSF, also has additional benefits for crop production, such as drought and salt tolerance, soil health [14], and disease suppression [15,16]. Mahmood et al. [17] demonstrated that the combined use of chicken manure and inorganic fertilizers at a rate of 150–85-50 kg ha^{-1} of NPK significantly increased corn grain yield compared to the individual use of organic or inorganic fertilizers in Pakistan. In Kenya, the application of BSF frass fertilizers at 7.5 t ha^{-1} mixed with N at 30, 60, and 100 kg ha^{-1} led to an increase in grain yields of 71–96 % during the short rainy season and 49–101 % during the long rainy season compared to the control (only BSF) [6]. This indicates that fertilizer application may be influenced by the growing season. In the Philippines, the highest yields of sweet corn at 12,500 and 15,810 kg ha^{-1} in husked and unhusked ears, respectively, were achieved by applying vermicompost at 20 t ha^{-1} and inorganic fertilizer at 84-63-42 kg ha^{-1} of NPK. This was because of the higher number of kernels (670) per ear compared to vermicompost without inorganic fertilizer application [18]. Previous studies have shown that the combination of vermicompost and the inorganic fertilizer NPSZnB substantially influences the phenology, growth, and yield parameters of corn [7]. We hypothesized that distinct fresh corn varieties under acidic sandy soil may respond differently to different types of fertilizer management. Therefore, this study aimed to evaluate the potential of vermicompost and BSF mixed with inorganic fertilizer on three different varieties of fresh corn grown under field conditions in Northeast Thailand. The information obtained from this study can help corn farmers reduce the use of inorganic fertilizers and accelerate the implementation of GAP to ensure food safety.

2. Materials and methods

2.1. Experimental site

Waxy and sweet corn are commonly grown in farmers' fields in the Chonnabot district, Khon Kaen province, in Northeast Thailand. Waxy corn is harvested faster than sweet corn. However, most planting areas in Northeast Thailand have acidic sandy soil, which is low in fertility, especially organic matter and available phosphorus. This research was conducted from June to September in 2022–2023 at the farmers' fields located in the Chanabot district, Khon Kaen province, Northeast Thailand. The experimental site is situated at latitude 16.4779°N and longitude 102.8558°N. The rainy season in this region starts in May and ends in October, followed by the winter and dry seasons. The total rainfall during the crop growth period in 2022 and 2023 is 847 mm and 850 mm, respectively. The maximum and minimum temperatures recorded were 29 °C and 27 °C in 2022 and 32 °C and 25 °C in 2023. Soil samples were collected from the experimental site before and after harvesting for chemical analyses. The study area predominantly consists of acidic sandy soil classified as Arenosol. Sandy soil contained more than 70 % sand and less than 15 % clay. Arenosols are characterised by little or no profile development and are commonly found in areas with sandy parent material. They can be acidic and are typically found in arid, semiarid, and coastal regions. According to the World Reference Base, sandy soils may also occur in the Regosol, Leptosol, and Fluvisol reference groups. Arenosols may have developed in the residual sand, weathering products of quartz-rich rocks, or recently deposited sand found in deserts and beaches [19].

2.2. Organic fertilizer analysis

Vermicompost was produced by Sila Farm, Earthworm Farm Khon Kaen in the Mueang Khon Kaen district of Khon Kaen Province. BSF is produced from waste products from a cricket (*Acheta domestics* L.) farm in the Baan Thum subdistrict of the Mueang Khon Kaen district, Khon Kaen province. Before starting the experiment, the chemical properties of the vermicompost and BSF samples were analysed. The pH was measured using a pH meter [20]. Organic matter (OM) was measured using the Walkley–Black method [21]. Electrical conductivity (EC) was measured using an EC meter [22]. Total N was measured as described by Bremner and Mulvaney [23]. The total P was measured using a wet digestion (nitric perchloric), Spectrophotometer [24,25]. Total K, Ca, Mg, Fe, Mn, Cu, and Zn were measured using wet digestion (nitric perchloric acid) and atomic absorption spectrophotometry [24]. Total Cr, As, Cd, and Pb contents were measured using wet digestion (nitric perchloric acid) and ICP-OES.

2.3. Soil sampling analysis before planting fresh corn

Soil samples were collected from different plots before planting fresh corn with various fertilizer applications. Ten points per plot were sampled at a depth of 0–30 cm and mixed, and preserved in plastic bags. The soil was analysed for chemical properties, including pH, OM, EC, total N by the Kjeldahl method, available P by Bray II and the molybdenum-blue method [26], exchangeable K, Ca, and Mg by 1 N NH_4OAc, pH 7, and the flame photometry method, and Fe, Mn, Cu, and Zn by diethylenetriaminepentaacetic acid (DTPA) pH 7.3, and atomic absorption spectrophotometry. Heavy metals, such as Cr, As, Cd, and Pb, were also measured. To measure soil nutrients, air-dried soil samples were crushed and passed through a 0.25 mm sieve.

2.4. Treatments and experimental setup

Four types of fertilizers were used as treatments, namely: F1) no fertilizer (control), F2) 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, F3) 6,250 kg ha^{-1} of BSF + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, and F4) 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}. The experiment followed a strip-plot design with three replicates. The experiment included three varieties of fresh corn: pink waxy, purple waxy, and sweet. The soil was prepared with cattle manure at a rate of 6.25 t ha^{-1} for two weeks before planting the three fresh corn varieties. Plant spacing was 65 cm between rows and 25 cm within plants, and the planting depth was 3–4 cm. The plot size was 2 × 10 m, with 12 plots per variety during the rainy season and water supply for field capacity if fresh corn suffered from intermittent drought. The fertilizer was applied twice during the experiment. The first application was performed 20 days after germination (DAG), and the second application was done 40–45 DAG. Weeding was performed manually with a hoe four weeks after planting and when needed. Data were collected during vegetative and reproductive stages. Harvesting was performed at the milking stage, which occurred at 60–65 DAG for waxy corn and 80–85 DAG for sweet corn. Soil samples were collected from different plots after planting fresh corn with various fertilizer applications to determine the soil chemical properties.

2.5. Corn growth and yield measurements

Plant height, soil plant analysis development (SPAD), and leaf area were measured in 20 plants per plot during the vegetative and reproductive stages of each fresh corn variety tested. The plant height was measured from the base of the stem to the youngest leaf. During the vegetative growth stage or 30–40 and 45–55 days after planting for waxy and sweet corn, respectively, SPAD measurements were taken on the second leaf from the top of 20 randomly selected plants from each plot, and the average was calculated. During the reproductive growth stage or 40–60 and 55–75 days after planting for waxy and sweet corn, respectively, data were collected from the leaves attached to the ear. Leaf area (LA) was estimated using a LI-Cor 3100 leaf area meter (LI-COR Inc, Lincoln, NE, USA). During the harvest stage, several parameters were recorded, including ear length, ear diameter, ear fresh weight, 1000 seed weight, leaf, husk leaf, stem dry weight, harvest index (HI), ash, protein, fat, fibre, carbohydrate, total N by the Bremner and Mulvaney method [18], total P by wet digestion and spectrophotometry [24,25], and K content by wet digestion (nitric perchloric) and atomic absorption spectrophotometry in the leaves [24], stem, and root parts.

2.6. Economic analysis

The cost of cultivation (Equation (1)), gross return (Equation (2)), and net income (Equation (3)) were computed to determine the economic performance of the three fresh corn varieties grown under the different fertilizer treatments. Price data for fertilizers and corn seeds were obtained from market prices in Thailand. Labour expenses (land preparation and planting) were calculated by recording the number of days at a rate of 13.50 USD per day (1 USD = 37.05 bath). The local prices of ear fresh weight for waxy corn = 0.41 USD kg^{-1} and sweet corn = 0.27 USD kg^{-1}, where the cost of BSF = 0.10 USD kg^{-1} and vermicompost = 0.41 USD kg^{-1}. Economic analysis was performed following the procedure described by Lawal et al. [27] with slight modifications based on the following costs:

$$\text{Cost of cultivation} = \text{seed material} + \text{fertilizers} + \text{planting area preparation} \tag{1}$$

$$\text{Gross return} = \text{Ear fresh weight} \times \text{the price of fresh corn} \tag{2}$$

$$\text{Net income} = \text{Gross return - cost of cultivation} \tag{3}$$

2.7. Statistical analysis

The collected data were analysed using an Analysis of Variance (ANOVA) with an F-test. If the results were significant, the Least Significant Difference (LSD) test was conducted at a 0.05 level of significance using Statistix 10 and Statistical Analysis System (SAS) software [28].

3. Results

3.1. Chemical properties of organic fertilizer and soil before planting fresh corn

The organic fertilizer BSF had the highest chemical parameters of OM, total N, and exchangeable K (Table 1). Conversely, vermicompost exhibited the highest chemical parameters of pH, EC, available P, and total Ca, Mg, Fe, Mn, Cu, and Zn. Both organic fertilizers contained heavy metals, such as Cr, As, and Cd, but their levels did not exceed the standards set by the Ministry of Agriculture in China, Canada, and the United States (USA) [29]. The soil samples collected before planting fresh corn showed significant differences in all chemical parameters, except Cd (Table 1). The soil was classified as sandy loam, and the experimental site was strongly acidic. The purple waxy corn experimental site tended to have the highest chemical parameters, including pH, OM, available P, exchangeable Ca, Mg, Fe, Cu, Zn, and heavy metals such As, Cd, and Pb. However, the total concentration of heavy metals in this experimental site was within the normal range for soils and non-toxic for plant growth, except for Cd, which exceeded the normal range (0.35 mg kg^{-1}) [30–32].

3.2. Soil chemical properties after planting fresh corn

Soil chemical parameters were analysed after harvesting the two fresh corn crops. These parameters were compared with the chemical properties of the soil before crop growth. Soil pH tended to increase after growing purple waxy and sweet corn but not at the experimental site for pink waxy corn (Tables 1 and 2). The soil used to cultivate purple waxy corn had the highest chemical parameters of OM, EC, total N, available P, exchangeable K, Fe, Zn, and heavy metals such as total Cr, As, and Pb (Table 2). However, sweet corn cultivation decreased the chemical characteristics of exchangeable Mg, Mn, Cu, Zn, total Cr, As, and Pb in the soil. The application of all fertilizers resulted in significant differences in soil chemical characteristics. Using vermicompost and BSF fertilizer tended to increase soil chemical parameters, such as pH, OM, EC, total N, available P, exchangeable K, Fe, total As, and Pb. Inorganic fertilizers also increased these parameters, except for soil pH and total N. However, exchangeable Ca, Mg, Mn, Cu, Zn, and total Cr tended to decrease compared with the soil before growth. Similarly, the application of inorganic fertilizer decreased soil parameters, such as pH, exchangeable Ca, Mg, Mn, Cu, Zn, and total Cr. The interaction between corn variety and fertilizer management also showed significant differences in soil chemical characteristics after crop growth. The application of all fertilizers tended to decrease the soil chemical parameters of pH, exchangeable Ca, Mg, Mn, Cu, Zn, and total Cd in the three fresh corn varieties, especially the inorganic and BSF fertilizers. In contrast, the soil chemical parameters of OM, EC, available P, exchangeable K, Fe, and total Pb tended to increase with the application of BSF. However, heavy rainfall during crop growth can cause changes in soil parameters when a large amount of water quickly moves through the soil and carries basic cations. Sandy soils are often the first to become acidic because water percolates rapidly through them, and they contain only a small reservoir of bases (buffer capacity) owing to their low clay and organic matter content.

3.3. Influence of different fertilizer managements on fresh corn growth

The first fertilizer was applied 20 days of germination until the vegetative stage at 30 DAG. Plant height and SPAD values of the three fresh corn varieties were significantly different (Table 3). Sweet corn grew faster than purple and pink waxy corn, with a plant height of 64.62 cm and a SPAD value of 48.87. Plant height was not significantly different, except for the SPAD value, under fertilizer application, compared with no fertilizer application. However, the interactions between variety and fertilizer management were not significantly different. At the flowering stage, different varieties showed significant differences in plant height and leaf area, but not in the SPAD value. The plant height of purple waxy corn (178.83 cm) was higher than pink waxy and sweet corn, while sweet corn showed the highest leaf area (6,058.60 cm^2) compared to other varieties. However, the application of all fertilizers did not significantly affect the plant height, SPAD, or leaf area. The application of inorganic fertilizer tended to promote these parameters compared with other fertilizer management methods. In contrast, the interaction between variety and fertilizer was significantly different between SPAD and leaf area. Pink waxy corn showed a significant difference in SPAD values under inorganic fertilizer application compared with no fertilizer application. In addition, sweet corn under 6,250 kg ha^{-1} of BSF +95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1} (F3), 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1} (F4), and 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1} (F2) management showed a significant difference in leaf area, accounting for 6,938.50, 6,777.60, and 6,192.60 cm^2 respectively.

3.4. Influence of different fertilizer managements on fresh corn yield

The three fresh types of corn showed significant differences in yield-related parameters, such as ear length, ear fresh weight, stem dry weight, ear diameter, leaf dry weight, and husk leaf dry weight (Table 4). Sweet corn had the highest fresh ear weight (7,529.20 kg ha^{-1} followed by pink and purple waxy corn. The application of 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1} (F4) and 6,250 kg ha^{-1} of BSF + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1} (F3) resulted in significant differences in the ear fresh weight, accounting for 6,569.90 and 6,275.40 kg ha^{-1}, respectively. In addition, the interaction between varieties and fertilizers showed no significant differences in any yield-related traits, except for the harvest index.

Table 1
Chemical properties of the organic fertilizers used and the experimental soil before planting fresh corn.

Organic phosphate	Chemical properties															
	pH	OM (%)	EC (dS m^{-1})	N (%)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Cr (mg kg^{-1})	As (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})
Vermicompost	6.86^{a}	40.31^{b}	0.92^{a}	1.30^{b}	0.62^{a}	0.36^{b}	1.75^{a}	0.50^{a}	3.57^{a}	0.10^{a}	24.17^{a}	206.86^{a}	7.50^{a}	2.60^{b}	0.84^{a}	2.34^{a}
Black Soldier Fly	6.22^{b}	50.89^{a}	0.62^{b}	2.06^{a}	0.43^{b}	1.06^{a}	0.49^{b}	0.19^{b}	0.03^{b}	0.00^{b}	0.05^{b}	0.04^{b}	6.73^{b}	3.17^{a}	0.30^{b}	1.75^{b}
F-test	**	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**
Experimental soil	pH	OM (%)	EC (dS m^{-1})	N (%)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Cr (mg kg^{-1})	As (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})
Purple waxy corn	5.06^{a}	0.54^{a}	0.03^{c}	0.03	6.63^{a}	77.93^{a}	237.36^{b}	45.53^{a}	50.36^{a}	4.25^{b}	0.20^{a}	1.23^{a}	19.42^{b}	1.04^{b}	0.53^{a}	3.45^{a}
Pink waxy corn	4.75^{c}	0.45^{b}	0.03^{b}	0.03	5.13^{b}	77.33^{a}	221.70^{c}	42.97^{b}	43.46^{b}	4.29^{b}	0.16^{b}	0.61^{b}	16.85^{c}	0.93^{b}	0.48^{b}	3.24^{ab}
Sweet corn	4.85^{b}	0.53^{a}	0.04^{a}	0.03	3.13^{c}	55.02^{c}	358.32^{a}	36.57^{c}	39.82^{c}	5.46^{a}	0.17^{b}	0.51^{c}	21.73^{a}	1.69^{a}	0.52^{ab}	3.05^{b}
F-test	**	**	**	ns	**	**	**	**	**	**	**	**	**	**	*	**

ns = not significant; * significant difference at $P < 0.05$; ** significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.

Table 2
Soil chemical characteristics before and after planting three fresh corn varieties.

Treatment	pH	OM (%)	EC (dS m^{-1})	N (%)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Cr (mg kg^{-1})	As (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})
Corn variety																
Purple waxy (V1)	5.53^{b}	0.64^{a}	0.06^{a}	0.04^{a}	30.01^{a}	109.48^{a}	181.01^{b}	32.84^{a}	64.87^{a}	3.19^{a}	0.10^{b}	1.01^{a}	21.87^{a}	1.86^{a}	0.45^{c}	3.80^{b}
Pink waxy (V2)	4.88^{c}	0.51^{b}	0.05^{b}	0.03^{b}	16.05^{b}	89.66^{b}	148.94^{c}	31.67^{a}	42,85^{b}	3.19^{a}	0.12^{a}	0.54^{b}	15.13^{c}	1.15^{b}	0.49^{b}	4.12^{a}
Sweet (V3)	5.61^{a}	0.51^{b}	0.03^{c}	0.04^{a}	12.22^{c}	86.03^{c}	189.44^{a}	27.02^{b}	37.79^{c}	3.09^{b}	0.08^{c}	0.53^{b}	15.45^{b}	1.20^{b}	0.52^{a}	3.66^{b}
F-test (V)	**	**	**	**	**	**	**	**	**	*	**	**	**	**	**	*
CV (%)	0.82	1.36	2.96	4.04	0.17	1.20	2.11	3.94	0.41	2.41	3.47	5.02	0.39	7.56	2.43	6.55
Fertilizer management																
Before growing (F0)	4.89^{d}	0.51^{d}	0.04^{d}	0.03^{d}	4.96^{e}	70.09^{e}	272.46^{a}	41.69^{a}	44.54^{d}	4.67^{a}	0.18^{a}	0.79^{a}	19.33^{a}	1.22^{d}	0.50^{a}	3.25^{d}
No fertilizer (F1)	5.64^{b}	0.54^{c}	0.03^{e}	0.04^{b}	6.33^{d}	77.60^{d}	127.90^{e}	23.67^{d}	49.07^{c}	2.72^{c}	0.09^{b}	0.75^{b}	15.58^{d}	1.33^{b}	0.50^{a}	3.88^{b}
Vermicompost (F2)	5.86^{a}	0.55^{c}	0.04^{c}	0.05^{a}	23.55^{b}	141.70^{a}	153.72^{c}	29.58^{c}	45.12^{d}	2.96^{b}	0.09^{bc}	0.74^{b}	17.45^{b}	1.35^{b}	0,49^{a}	3.72^{c}
BSF (F3)	5.51^{c}	0.60^{a}	0.07^{b}	0.03^{c}	42.33^{a}	104.99^{b}	162.20^{b}	38.22^{b}	52.50^{a}	2.74^{c}	0.08^{c}	0.75^{b}	15.70^{c}	1.26^{c}	0.50^{a}	4.43^{a}
Inorganic fertilizer (F4)	4.82^{e}	0.58^{b}	0.08^{a}	0.03^{c}	19.96^{c}	80.91^{c}	149.37^{d}	19.41^{e}	51.26^{b}	2.69^{c}	0.07^{d}	0.44^{c}	19.35^{a}	1.87^{a}	0.44^{b}	4.01^{b}
F-test (F)	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
CV (%)	0.66	0.86	2.96	4.04	0.17	2.05	1.41	3.35	1.85	1.82	3.62	2.54	0.57	2.28	3.25	3.55
V × F																
V1 × F0	5.06^{f}	0.55^{c}	0.03^{g}	0.03^{e}	6.63^{k}	77.93^{h}	237.36^{b}	45.53^{a}	50.36^{e}	4.25^{b}	0.20^{a}	1.23^{b}	19.42^{e}	1.03^{fgh}	0.53^{b}	3.45^{m}
V1 × F1	5.08^{f}	0.60^{d}	0.03^{g}	0.03^{e}	6.75^{j}	62.57^{j}	129.00^{h}	24.48^{g}	69.60^{b}	3.00^{ef}	0.07^{g}	1.46^{a}	21.42^{d}	1.95^{c}	0.43^{h}	4.05^{d}
V1 × F2	6.72^{a}	0.66^{c}	0.03^{g}	0.08^{a}	44.17^{b}	210.75^{a}	199.44^{d}	30.56^{f}	61.32^{d}	3.21^{d}	0.09^{f}	0.88^{c}	24.68^{a}	2.02^{bc}	0.48^{f}	3.95^{f}
V1 × F3	5.90^{d}	0.71^{a}	0.09^{c}	0.04^{c}	65.00^{a}	101.07^{d}	166.80^{f}	41.87^{c}	78.00^{a}	2.85^{g}	0.09^{f}	0.87^{c}	24.28^{b}	2.13^{ab}	0.45^{g}	3.85^{h}
V1 × F4	4.92^{g}	0.69^{b}	0.13^{a}	0.04^{c}	27.50^{e}	95.10^{f}	172.44^{e}	21.78^{h}	65.07^{c}	2.86^{h}	0.06^{gh}	0.60^{fg}	19.53^{e}	2.18^{a}	0.36	3.68^{j}
V2 × F0	4.75^{i}	0.44^{i}	0.04^{f}	0.03^{e}	5.13^{m}	77.33^{h}	221.70^{c}	42.98^{b}	43.46^{fg}	4.29^{b}	0.16^{c}	0.61^{fg}	16.85^{f}	0,92^{hi}	0.48^{f}	3.24
V2 × F1	5.29^{e}	0.49^{g}	0.03^{g}	0.03^{e}	6.75^{j}	71.37^{i}	120.30^{i}	24.69^{g}	42.61^{gh}	2.60^{h}	0.14^{d}	0.47^{h}	9.89^{k}	1.10^{fg}	0.52^{c}	4.10^{c}
V2 × F2	4.75^{i}	0.49^{g}	0.07^{d}	0.03^{e}	18.00^{f}	96.66^{ef}	121.26^{i}	32.24^{e}	42.39^{gh}	3.09^{d}	0.11^{e}	0.63^{f}	12.01^{j}	0.90^{hi}	0.49^{e}	3.43^{k}
V2 × F3	4.68^{j}	0.53^{f}	0.10^{b}	0.03^{e}	32.50^{c}	126.21^{b}	117.83^{i}	38.34^{c}	41.17^{hi}	2.47^{i}	0.11^{e}	0.59^{g}	12.82^{i}	0.77^{j}	0.54^{a}	5.41^{a}
V2 × F4	4.95^{g}	0.60^{d}	0.05^{e}	0.03^{e}	17.87^{g}	76.74^{h}	163.62^{f}	20.09^{h}	44.61^{f}	3.49^{c}	0.09^{f}	0.41^{i}	24.11^{b}	2.06^{ab}	0.45^{g}	4.42^{b}
V3 × F0	4.86^{h}	0.53^{f}	0.04^{f}	0.03^{d}	5.13^{m}	55.03^{k}	358.32^{a}	36.57^{c}	39.82^{ij}	5.46^{a}	0.18^{b}	0.52^{h}	21.73^{c}	1.68^{d}	0.52^{c}	3.06^{n}
V3 × F1	6.53^{b}	0.53^{f}	0.02^{h}	0.06^{b}	5.50^{l}	98.85^{de}	134.40^{h}	21.83^{h}	35.02^{k}	2.56^{hi}	0.06^{gh}	0.31^{j}	15.43^{g}	0.96^{ghi}	0.54^{a}	3.50^{l}
V3 × F2	6.09^{c}	0.48^{h}	0.02^{h}	0.03^{e}	8.50^{i}	117.69^{c}	140.46^{g}	25.93^{g}	31.64^{l}	2.59^{hi}	0.06^{hi}	0.71^{e}	15.67^{g}	1.12^{f}	0.51^{d}	3.79^{i}
V3 × F3	5.95^{d}	0.55^{c}	0.03^{g}	0.03^{e}	29.50^{d}	87.69^{g}	201.96^{d}	34.44^{d}	38.33^{j}	2.90^{fg}	0,05^{j}	0.80^{d}	10.02^{k}	0.88^{ij}	0.54^{a}	4.04^{e}
V3 × F4	4.59^{k}	0.44^{i}	0.05^{e}	0.03^{e}	14.50^{h}	70.89^{i}	112.04^{j}	16.35^{i}	44.11^{f}	1.93^{j}	0.05^{ij}	0.32^{j}	14.40^{h}	1.37^{e}	0.52^{c}	3.92^{g}
F-test (V × F)	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
CV (%)	0.54	1.70	2.96	4.04	0.17	1.90	1.65	2.50	1.81	2.20	3.84	3.32	1.00	6.25	1.43	2.87

CV, coefficient of variation; *, significant difference at $P < 0.05$; **, significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.
F1: no fertilizer (control); F2: 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F3: 6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F4: 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}.

Table 3
Plant growth at the vegetative and reproductive stages of three fresh corn varieties grown under different fertilizer managements.

Treatment	Vegetative stage		Reproductive stage		
	Plant height (cm)	SPAD	Plant height (cm)	SPAD	Leaf area (cm^2)
Corn variety					
Purple waxy (V1)	42.26^{b}	41.21^{b}	178.83^{a}	52.97	2,465.20^{b}
Pink waxy (V2)	37.79^{b}	40.36^{b}	135.07^{c}	50.23	2,577.50^{b}
Sweet (V3)	64.62^{a}	48.87^{a}	159.48^{b}	52.76	6,058.60^{a}
F-test (V)	*	*	*	ns	**
CV (%)	33.06	12.42	10.03	8.34	44.85
Fertilizer management					
No fertilizer (F1)	41.02	38.78^{b}	140.90	43.00	2,668.50
Vermicompost (F2)	43.70	43.36^{a}	157.04	53.11	3,651.70
BSF (F3)	46.25	45.76^{a}	164.44	55.22	3,925.20
Inorganic fertilizer (F4)	61.92	46.03^{a}	168.79	56.62	4,556.20
F-test (F)	ns	*	ns	ns	ns
CV (%)	29.68	7.60	10.80	16.80	30.54
V × F					
V1 × F1	41.03	38.35	177.83	43.89^{ab}	2,123.20^{cd}
V1 × F2	31.57	40.57	166.27	54.42^{ab}	1,935.10^{cd}
V1 × F3	35.39	42.65	182.13	57.13^{ab}	2,457.80^{bcd}
V1 × F4	61.05	43.29	189.10	56.44^{ab}	3,344.70^{bcd}
V2 × F1	32.95	36.40	104.07	41.77^{b}	1,556.70^{d}
V2 × F2	37.67	40.97	143.73	49.97^{ab}	2,827.50^{bcd}
V2 × F3	29.33	40.39	139.67	51.03^{ab}	2,379.40^{bcd}
V2 × F4	51.20	43.67	152.80	58.19^{a}	3,546.30^{bc}
V3 × F1	49.07	41.60	140.80	43.36^{ab}	4,325.60^{b}
V3 × F2	61.87	48.52	161.13	54.95^{ab}	6,192.60^{a}
V3 × F3	74.03	54.23	171.53	57.49^{ab}	6,938.50^{a}
V3 × F4	73.51	51.13	164.47	55.24^{ab}	6,777.60^{a}
F-test (V × F)	ns	ns	ns	*	*
CV (%)	20.61	7.97	7.61	3.70	12.76

CV = coefficient of variation; ns = not significant; * significant difference at $P < 0.05$; ** significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.
F1: no fertilizer (control); F2: 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F3: 6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, F4: 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}.

3.5. The correlation coefficients of agronomic traits and economic yield in fresh corn

The correlations of agronomic traits and economic yield in the three fresh corn varieties under different fertilizer management regimes and the 11 traits evaluated in this study are shown in Table 5. A total of 40 significant correlations were found ($p < 0.05$) and ($p < 0.01$), of which were five negative and fifty were positive. They were grouped according to the value of correlation among traits: low correlation (≤0.35), moderate correlation (0.36–0.70), and strong correlation (≥0.71) [33] with 17, 27, and 11 correlations classified as low, moderate, and strong, respectively. Plant height showed a moderate positive correlation with SPAD value, husk leaf dry weight, stem dry weight, and ear length. The leaf area, husk leaf dry weight, stem dry weight, ear length, ear diameter, and no. of the seed ear^{-1} traits showed strong positive correlations with fresh ear weight. As the values of certain agronomic traits increased, the economic yield also tended to increase. These traits indicate the ability of plants to efficiently use available resources to produce biomass, including fresh ear weight. Leaf dry weight showed a moderately positive correlation with leaf area, ear length, and no. of seeds ear^{-1} but had low negative correlations with 1000 seeds weight.

3.6. Influence of different fertilizer managements on the nutritional values of fresh corn

The corn variety was significant for ash, protein, fat, fibre, and carbohydrate content (Table 6). Sweet corn had the highest protein, fat, and fibre contents at 14.48 %, 4.74 %, and 1.30 %, respectively. On the other hand, pink waxy corn showed the highest carbohydrate and ash contents of 80.56 % and 0.88 %, respectively. In addition, different fertilizer applications resulted in substantial differences in all nutritional values (Table 6). The application of 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1} (F4) resulted in the highest protein, fat, and fibre contents of 12.04 %, 4.62 %, and 0.91 %, respectively. However, no fertilizer application led to a significantly higher difference in carbohydrate content, 79.34 %. The interaction between different corn varieties and fertilizer application also showed significant differences in nutritional values (Table 6). Sweet corn treated with 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1} (F4) showed the highest protein, fat, and fibre contents of 17.75 %, 5.88 %, and 0.91 %, respectively. In contrast, the interaction between pink waxy corn and no fertilizer resulted in the highest carbohydrate content.

Table 4
Yield components and harvest index (HI) of three fresh corn varieties grown under different fertilizer managements.

Treatment	Ear length (cm)	Ear diameter (cm)	Ear fresh weight (kg ha^{-1})	1000 seeds weight (g)	Leaf dry weight (kg ha^{-1})	Husk leaf dry weight (kg ha^{-1})	Stem dry weight (kg ha^{-1})	HI
Corn variety								
Purple waxy (V1)	14.75^{b}	3.82^{b}	4,362.90^{b}	85.10	848.30^{b}	675.25^{b}	1,369.50^{b}	0.14
Pink waxy (V2)	13.91^{b}	4.23^{a}	4,654.70^{b}	89.20	875.00^{b}	588.69^{b}	1,089.20^{b}	0.18
Sweet corn (V3)	18.48^{a}	4.27^{a}	7,529.20^{a}	69.30	1,379.20^{a}	854.49^{a}	1,874.40^{a}	0.09
F-test (V)	**	*	**	ns	*	*	**	ns
CV (%)	8.91	5.41	13.86	19.36	17.83	16.05	22.29	46.91
Fertilizer management								
No fertilizer (F1)	13.70^{c}	3.68^{c}	3,985.80^{c}	6.32	815.00	600.40^{c}	1,145.40^{b}	0.13
Vermicompost (F2)	15.72^{b}	4.03^{bc}	5,231.20^{b}	7.67	1,115.60	689.24^{bc}	1,507.60^{a}	0.12
BSF (F3)	16.60^{ab}	4.21^{ab}	6,275.40^{a}	6.76	1,056.10	723.35^{ab}	1,512.00^{a}	0.12
Inorganic fertilizer (F4)	16.85^{a}	4.49^{a}	6,569.90^{a}	11.29	1,150.00	811.59^{a}	1,612,50^{a}	0.17
F-test (F)	**	*	**	ns	ns	*	*	ns
CV (%)	6.03	8.06	13.73	24.98	24.27	14.69	17.56	25.81
V × F								
V1 × F1	12.50	3.29	2,807.40	5.66	681.60	567.00	1,132.10	0.08^{i}
V1 × F2	14.54	3.88	4,525.90	10.01	777.20	649.30	1,221.50	0.12^{f}
V1 × F3	15.09	3.88	4,666.60	7.60	951.40	751.40	1,648.90	0.12^{f}
V1 × F4	16.88	4.21	5,451.80	10.77	983.00	733.30	1,475.50	0.20^{c}
V2 × F1	12.75	4.16	4,027.90	9.45	578.40	473.00	721.50	0.22^{a}
V2 × F2	14.25	4.06	4,519.00	6.25	1,105.30	618.70	1,250.60	0.13^{e}
V2 × F3	14.30	4.13	4,771.90	6.60	821.00	632.70	1,143.40	0.14^{d}
V2 × F4	14.34	4.56	5,299.90	13.37	995.40	630.40	1,241.50	0.21^{b}
V3 × F1	15.84	3.59	5,122.10	5.17	1,185.20	761.20	1,582.70	0.12^{f}
V3 × F2	18.36	4.15	6,648.80	6.73	1,464.20	799.70	2,050.80	0.07^{j}
V3 × F3	20.40	4.63	9,387.80	6.09	1,395.80	785.90	1,743.70	0.11^{g}
V3 × F4	19.32	4.70	8,958.00	9.73	1,471.60	1,071.10	2,120.50	0.10^{h}
F-test (V × F)	ns	ns	ns	ns	ns	ns	ns	*
CV (%)	6.30	7.24	16.91	23.00	20.12	19.23	15.82	28.01

CV = coefficient of variation; ns = not significant; * significant difference at $P < 0.05$; ** significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.
F1: no fertilizer (control); F2: 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F3: 6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, F4: 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}.

3.7. Influence of different fertilizer managements on the N, P, and K content of fresh corn

The leaves of the three fresh corn varieties grown with different fertilizers contained high levels of nitrogen (N), phosphorus (P), and potassium (K). Sweet corn had a significant effect on the accumulation of N and P, which is beneficial for biological and economic yields (Table 7). Among the different fertilizer applications, the one with 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1} (F4) resulted in the highest N content in the leaf, stem, and root parts. In contrast, the application of 6,250 kg ha^{-1} of BSF +95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1} (F3) showed the highest P and K content. In addition, the interaction between variety and fertilizer showed a significant difference in the N, P, and K contents of the leaves, stems, and roots. The sweet corn variety had the highest N content in the leaves when treated with inorganic fertilizer (190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}; F4). In contrast, purple and pink waxy corn varieties showed the highest P and K contents in the leaf part when treated with 6,250 kg ha^{-1} of BSF +95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1} (F3).

3.8. Net income and cost of cultivation of fresh corn using different fertilizer managements

The cost of cultivation with vermicompost management tends to be more expensive than with other treatments when the cost of BSF at 0.10 USD kg^{-1} is cheaper than vermicompost at 0.41 USD kg^{-1}. The economic returns from fresh corn produced using different fertilizer management methods are listed in Table 8. Three fresh corn samples grown using inorganic fertilizer (F4) and BSF mixed with inorganic fertilizer (F3) generated the highest net income, which was not different from using no fertilizer (F1), but higher than the use of vermicompost mixed with inorganic fertilizer (F2). The application of inorganic fertilizer (F4) resulted in a higher net return in purple waxy and sweet corn, followed by BSF mixed with inorganic fertilizer (F3) and no fertilizer (F1). Meanwhile, the application of no fertilizer (F1) resulted in a higher net return in pink waxy corn, followed by inorganic fertilizer (F4) and BSF mixed with inorganic fertilizer (F3).

Table 5
The matrix correlation coefficients of agronomic traits and economic yield in fresh corn.

Agronomic traits	Plant height (cm)	SPAD value	Leaf area (cm^2)	Ear length (cm)	Ear diameter (cm)	No. of seed ear^{-1} (seeds)	Leaf dry weight ($kg\ ha^{-1}$)	Husk leaf dry weight ($kg\ ha^{-1}$)	Stem dry weight ($kg\ ha^{-1}$)	1000 seeds weight (g)	Ear fresh weight ($kg\ ha^{-1}$)
Plant height (cm)	1										
SPAD value	0.44**	1									
Leaf area (cm^2)	0.27^{ns}	0.40*	1								
Ear length (cm)	0.38*	0.46**	0.78**	1							
Ear diameter (cm)	0.04^{ns}	0.41*	0.43**	0.52**	1						
No. of seed ear^{-1} (seeds)	0.34*	0.49**	0.62**	0.71**	0.39*	1					
Leaf dry weight ($kg\ ha^{-1}$)	0.16^{ns}	0.27^{ns}	0.56**	0.53**	0.29^{ns}	0.40*	1				
Husk leaf dry weight ($kg\ ha^{-1}$)	0.36*	0.43**	0.57**	0.65**	0.45**	0.64**	0.50**	1			
Stem dry weight ($kg\ ha^{-1}$)	0.53**	0.46**	0.72**	0.74**	0.35*	0.57**	0.60**	0.85**	1		
1000 seeds weight (g)	0.16^{ns}	0.15^{ns}	-0.12^{ns}	-0.01^{ns}	0.44**	-0.27^{ns}	-0.08^{ns}	0.02^{ns}	-0.02^{ns}	1	
Ear fresh weight ($kg\ ha^{-1}$)	0.22^{ns}	0.45**	0.78**	0.89**	0.73**	0.77**	0.50**	0.72**	0.72**	0.05^{ns}	1

ns = not significant; * significant difference at $P < 0.05$; ** significant difference at $P < 0.01$.
The value of correlation: low (≤0.35), moderate (0.36–0.70), and strong (≥0.71) [33].

4. Discussion

4.1. Vermicompost and BSF fertilizers enhance the chemical properties of acidic sandy soil

The application of different types of fertilizers significantly affected the chemical properties of acidic sandy soils. The use of vermicompost and BSF fertilizers tended to increase the pH level, OM content, total N, available P, exchangeable K, and Fe in the soil. In contrast, the long-term use of inorganic fertilizers can reduce the pH level and some macro- and micronutrients. However, the combined use of both fertilizers could increase the EC and heavy metals such as As and Pb in the soil. Tufa [7] reported that the use of vermicompost fertilizer can improve the soil's structure, i.e., soil porosity, OM content, pH, and total N. Since soil pH is crucial for dissolving and providing available nutrients for plants to uptake, Sebayang et al. [34] suggested that the combination of vermicompost and BSF larvae can increase the effectiveness of soil organic matter. However, soil with no fertilizer application showed remarkably higher exchangeable Zn and heavy metals such as Cr and Pb, compared to soil before and after using fertilizers. These results imply that the soil already had a high initial content of these toxic heavy metals, possibly derived from fertilizers applied to the previous crop [35, 36].

4.2. Vermicompost and BSF fertilizers enhance plant growth of fresh corn

Thirty days after germination or 10 days after the first fertilizer application, the plant height and leaf SPAD were not affected by the fertilizer management, except for leaf SPAD in sweet corn. The decomposition and release of organic fertilizers are time-consuming and can lead to insufficient N demand [6]. Nitrogen is crucial for plant growth as it is a constituent of amino acids, proteins, and chlorophyll, which are important in the photosynthesis process [37]. When N availability is low, it can inhibit plant growth, and leaves show chlorosis due to a decrease in chlorophyll [38]. Therefore, the combination of inorganic fertilizers with organic phosphate can enhance fresh corn production during the early crop growth stage. Lukiwati et al. [39] found that the use of organic fertilizers could provide a similar effect to that of inorganic NPK on plant height and biomass. At the flowering stage, the results showed that the application of all fertilizers affected the leaf area compared to no fertilizer application in the three fresh corn varieties, with optimum results obtained in sweet corn.

Table 6
Nutritional values of three fresh corn varieties grown under different fertilizer managements.

Treatment	Ash (%)	Protein (%)	Fat (%)	Fiber (%)	Carbohydrate (%)
Corn variety					
Purple waxy (V1)	0.80^{c}	9.46^{b}	3.22^{c}	0.58^{b}	79.70^{b}
Pink waxy (V2)	0.88^{a}	8.71^{c}	4.32^{b}	0.30^{c}	80.56^{a}
Sweet (V3)	0.83^{b}	14.48^{a}	4.74^{a}	1.30^{a}	70.88^{c}
F-test (V)	**	**	**	**	**
CV (%)	0.90	1.14	2.54	1.34	0.24
Fertilizer management					
No fertilizer (F1)	0.82^{c}	9.33^{d}	4.27^{b}	0.53^{d}	79.34^{a}
Vermicompost (F2)	0.79^{d}	10.76^{c}	3.57^{d}	0.81^{b}	76.72^{b}
BSF (F3)	0.88^{a}	11.40^{b}	3.92^{c}	0.64^{c}	76.75^{b}
Inorganic fertilizer (F4)	0.85^{b}	12.04^{a}	4.62^{a}	0.91^{a}	75.37^{c}
F-test (F)	**	**	**	**	**
CV (%)	0.94	1.06	3.27	1.46	0.30
V × F					
V1 × F1	0.82^{d}	8.47^{h}	3.46^{g}	0.55^{f}	81.20^{b}
V1 × F2	0.74^{g}	10.20^{e}	2.68^{i}	0.92^{d}	77.08^{f}
V1 × F3	0.83^{cd}	9.93^{f}	3.23^{h}	0.36^{h}	80.04^{d}
V1 × F4	0.80^{e}	9.24^{g}	3.54^{g}	0.47^{g}	80.49^{c}
V2 × F1	0.88^{b}	7.29^{i}	4.58^{c}	0.32^{i}	82.06^{a}
V2 × F2	0.82^{d}	8.61^{h}	4.07^{ef}	0.33^{i}	80.52^{c}
V2 × F3	0.91^{a}	9.81^{f}	4.22^{de}	0.28^{j}	79.14^{e}
V2 × F4	0.89^{b}	9.13^{g}	4.42^{cd}	0.24^{k}	80.51^{c}
V3 × F1	0.76^{f}	12.24^{d}	4.78^{b}	0.73^{e}	74.74^{g}
V3 × F2	0.80^{e}	13.45^{c}	3.95^{f}	1.16^{c}	72.57^{h}
V3 × F3	0.89^{ab}	14.45^{b}	4.32^{d}	1.28^{b}	71.07^{i}
V3 × F4	0.84^{c}	17.75^{a}	5.88^{a}	2.01^{a}	65.12^{j}
F-test (V × F)	**	**	**	**	**
CV (%)	1.35	0.95	2.26	1.75	0.22

CV = coefficient of variation; ** significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.
F1: no fertilizer (control); F2:6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F3:6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, F4:190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}.

4.3. Vermicompost and BSF fertilizers enhance yield components of fresh corn

Our study revealed that the application of organic phosphate along with inorganic fertilizer significantly improved the yield of fresh corn under acidic sandy soil. The use of inorganic fertilizer (F4) and BSF with inorganic fertilizer (F3) resulted in a marked increase in yield components, particularly in ear fresh weight, with 6,569.90 and 6,275.40 kg ha^{-1}, respectively. Previous reports indicated that BSF frass provided better results regarding corn yield compared to other organic fertilizers, such as chicken manure, biochar, and rock phosphate [6]. However, there was no significant difference in 1000 seed weight among the corn varieties and fertilizer applications. Generally, an increase in plant growth leads to an increase in corn yield. Thus, the combination of organic phosphate with inorganic fertilizers can provide optimal ear fresh corn yield compared to no fertilizer or only inorganic fertilizer.

4.4. Vermicompost and BSF fertilizers enhance nutritional values of fresh corn

Our study also examined the nutritional values of three fresh corn varieties under different nitrogen fertilizer applications. The results showed that corn kernels without any fertilizer (F1) had the highest carbohydrate content. An increase in nitrogen led to a remarkable decrease in soluble carbohydrates in the fresh corn kernels. Almodares et al. [40] noted that increasing the use of urea fertilizer from 50 kg ha^{-1} to 200 kg ha^{-1} resulted in a substantial decrease in soluble carbohydrates. Regarding the nitrogen fixation pathway, some of the intermediate metabolites in the tricarboxylic acid (TCA) cycle are used to synthesize amino acids and proteins. Tanga et al. [14] reported that the control treatment, which was without nitrogen fertilizer, produced a substantially higher carbohydrate content than the other fertilizer treatments in the corn kernels of variety H517 evaluated in Kenya. In contrast, the application of nitrogen fertilizer resulted in an increase in protein and fibre content and a decrease in soluble carbohydrates. However, this may affect the palatability and digestibility of fresh corn. Our study suggests that further testing is required to determine the optimum level of nitrogen fertilizer that can increase protein and soluble carbohydrates while decreasing fibre content in fresh corn. We found that the application of 6,250 kg ha^{-1} BSF +95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1} (F3) provided more fresh corn yield, protein content, and low fiber content compare to vermicompost fertilizer. This corroborates the results of a previous study by Beesigamukama et al. [6], which highlighted BSF as a promising and sustainable alternative organic fertilizer that can enhance corn production under the GAP standard. They observed that BSF applied at 30 and 60 kg N ha^{-1} resulted in a significantly higher nitrogen fertilizer equivalence (NFE) than all commercial organic fertilizers.

The production of secondary metabolites in corn depends on various factors such as genetics, environmental conditions

Table 7
Total N, P, K contents of three fresh corn varieties grown under different fertilizer managements.

Treatment	Leaf			Stem			Root		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
Corn variety									
Purple waxy (V1)	1.17^{b}	0.160^{b}	2.51^{a}	0.95^{a}	0.14^{a}	2.49^{b}	1.25^{a}	0.07^{a}	1.77^{a}
Pink waxy (V2)	1.21^{b}	0.160^{b}	1.69^{c}	0.86^{b}	0.10^{b}	2.51^{a}	0.73^{b}	0.05^{b}	1.21^{b}
Sweet (V3)	2.05^{a}	0.163^{a}	1.86^{b}	0.54^{c}	0.09^{c}	1.33^{c}	0.62^{c}	0.06^{b}	0.85^{c}
F-test (V)	**	*	**	**	**	**	**	**	**
CV (%)	0.63	1.03	6.56	1.94	1.52	0.78	1.77	0.00	0.44
Fertilizer management									
No fertilizer (F1)	1.75^{b}	0.11^{d}	1.86^{b}	0.56^{d}	0.08^{d}	2.04^{b}	0.54^{d}	0.04^{c}	1.29^{b}
Vermicompost (F2)	0.97^{c}	0.16^{c}	1.96^{b}	0.70^{c}	0.10^{c}	1.96^{d}	0.81^{c}	0.06^{b}	1.19^{c}
BSF (F3)	0.82^{c}	0.21^{a}	2.13^{a}	0.92^{b}	0.13^{a}	2.42^{a}	1.03^{b}	0.08^{a}	1.33^{a}
Inorganic fertiizer (F4)	2.36^{a}	0.17^{b}	2.12^{a}	0.97^{a}	0.11^{b}	2.00^{c}	1.11^{a}	0.06^{b}	1.29^{b}
F-test (F)	**	**	*	**	**	**	**	**	**
CV (%)	1.45	1.03	6.94	1.44	1.52	0.33	1.82	0.00	0.62
V × F									
V1 × F1	2.02^{f}	0.12^{j}	2.80^{a}	0.77^{f}	0.12^{c}	2.79^{c}	0.83^{f}	0.05^{d}	1.89^{b}
V1 × F2	0.21^{k}	0.17^{e}	2.01^{b}	0.85^{e}	0.11^{d}	1.97^{h}	1.28^{c}	0.07^{b}	1.54^{d}
V1 × F3	0.14^{l}	0.21^{b}	2.61^{a}	1.08^{c}	0.20^{a}	2.83^{b}	1.48^{a}	0.09^{a}	1.66^{c}
V1 × F4	2.34^{b}	0.14^{h}	2.63^{a}	1.12^{b}	0.13^{b}	2.35^{e}	1.43^{b}	0.06^{c}	1.97^{a}
V2 × F1	1.64^{g}	0.07^{j}	1.16^{d}	0.56^{g}	0.08^{f}	2.23^{g}	0.50^{j}	0.03^{e}	1.28^{f}
V2 × F2	0.61^{i}	0.18^{d}	2,01^{b}	0.75^{f}	0.11^{d}	2.62^{d}	0.69^{h}	0.06^{c}	1.12^{g}
V2 × F3	0.28^{j}	0.23^{a}	1.81^{bc}	1.17^{a}	0.10^{e}	2.92^{a}	1.01^{e}	0.08^{a}	1.41^{e}
V2 × F4	2.31^{c}	0.16^{f}	1.78^{bc}	0.96^{d}	0.11^{d}	2.28^{f}	0.72^{g}	0.04^{d}	1.02^{h}
V3 × F1	1.59^{h}	0.13^{i}	1.62^{c}	0.35^{i}	0.06^{h}	1.11^{l}	0.29^{l}	0.04^{d}	0.70^{l}
V3 × F2	2.09^{d}	0.14^{g}	1.87^{b}	0.49^{h}	0.08^{g}	1.30^{k}	0.45^{k}	0.06^{c}	0.90^{j}
V3 × F3	2.06^{e}	0.18^{d}	1.97^{b}	0.49^{h}	0.11^{d}	1.53^{i}	0.59^{i}	0.06^{c}	0.92^{i}
V3 × F4	2.44^{a}	0.20^{c}	1.97^{b}	0.83^{e}	0.10^{e}	1.37^{j}	1.16^{d}	0.07^{b}	0.88^{k}
F-test (V × F)	**	**	**	**	**	**	**	**	**
CV (%)	0.95	1.03	6.60	2.09	1.52	0.40	1.54	0.00	0.50

CV, coefficient of variation; *, significant difference at $P < 0.05$; **, significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.
F1: no fertilizer (control); F2: 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F3: 6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, F4: 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}.

Table 8
Net income and gross margin generated from fresh corn produced under different fertilizer managements.

Treatment	Yield (kg ha^{-1})	Cost of cultivation (USD ha^{-1})	Gross return (USD ha^{-1})	Net return (USD ha^{-1})
Purple waxy corn				
No fertilizer (F1)	2,807.40^{b}	210.25	1,151.03^{b}	940.78^{a}
Vermicompost (F2)	4,525.90^{ab}	2,936.04	1,855.62^{ab}	−1,080.42^{b}
BSF (F3)	4,666.60^{ab}	937.85	1,913.31^{ab}	975.46^{a}
Inorganic fertilizer (F4)	5,451.80^{a}	796.67	2,235.24^{a}	1,438.57^{a}
F-test	*		*	**
Pink waxy corn				
No fertilizer (F1)	4,027.90^{b}	205.90	1,651.44^{b}	1,445.54^{a}
Vermicompost (F2)	4,519.00^{ab}	2,931.70	1,852.79^{ab}	−1,078.91^{b}
BSF (F3)	4,771.90^{ab}	933.50	1,956.48^{ab}	1,022.98^{a}
Inorganic fertilizer (F4)	5,299.90^{a}	792.33	2,172.96^{a}	1,380.63^{a}
F-test	*		*	**
Sweet corn				
No fertilizer (F1)	5,122.10^{b}	198.95	1,382.97^{b}	1,184.02^{a}
Vermicompost (F2)	6,648.80^{ab}	2,924.75	1,795.18^{ab}	−1,129.57^{b}
BSF (F3)	9,387.80^{a}	926.55	2,534.71^{a}	1,608.16^{a}
Inorganic fertilizer (F4)	8,958.00^{a}	785.38	2,418.66^{a}	1,633.28^{a}
F-test	**		**	**

CV, coefficient of variation; *, significant difference at $P < 0.05$; **, significant difference at $P < 0.01$.
Different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at $P < 0.05$.
F1: no fertilizer (control); F2: 6,250 kg ha^{-1} of vermicompost + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}; F3: 6,250 kg ha^{-1} of black soldier fly (BSF) + 95.31 kg N ha^{-1} + 23.44 kg P ha^{-1} + 23.44 kg K ha^{-1}, F4: 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1}.
Local price of waxy corn = 0.41 USD kg^{-1} and sweet corn = 0.27 USD kg^{-1}. The cost of cultivation includes seeding material, fertilizer, and planting area preparation.

(temperature, light, water, and nutrients), agricultural management practices (fertilizer, growing season, and harvest time), post-harvest storage, and biotic stress (weeds, insects, and plant diseases) [41]. Lycopene biosynthesis is strongly inhibited at temperatures below 12 °C and completely stops at temperatures above 32 °C. The effects of light, with the exception of those of vitamin E, have been extensively studied. Variations in nutrient levels resulting from different fertilizers can lead to differences in the concentrations of C, N, P, K, and Ca in plants, consequently affecting secondary metabolites [42]. Excessive use of inorganic fertilizers may decrease antioxidant levels, whereas organic fertilizers has been shown to enhance the production of plant secondary metabolites [43]. When N is readily available, plants have high protein content. Conversely, limited N availability causes a shift in metabolism towards carbon-containing compounds, such as starch, cellulose, phenolics, and terpenoids [44]. Our results indicate that the application of 190.63 kg N ha^{-1} + 46.88 kg P ha^{-1} + 46.88 kg K ha^{-1} (F4) resulted in the highest protein content at 17.75 % in sweet corn kernels. In contrast, the interaction between pink waxy corn and no fertilizer resulted in the highest carbohydrate content. A recent study by Ibrahim et al. [45] demonstrated that the application of chicken manure and 90 kg ha^{-1} N improved secondary metabolite production in *Labisia pumila*. However, excess N reduces the levels of secondary metabolites and the antioxidant activity of this herb. These results suggest that organic and inorganic fertilizers enhance the production of secondary metabolites in plants.

4.5. The correlation between agronomic traits and economic yield in fresh corn

The correlations between agronomic traits and economic yield contribute to improved agricultural productivity and profitability [46]. Plant height showed a moderate positive correlation with SPAD value, husk leaf dry weight, stem dry weight, and ear length. A higher chlorophyll content is usually more efficient for photosynthesis to produce the necessary carbohydrates and other compounds, allowing the plant more energy for leaf and stem growth. In contrast, the leaf area showed a strong positive correlation with ear diameter and fresh ear weight. A larger leaf area increases the photosynthetic capacity of a plant, as there is more surface area available to capture sunlight and convert it into energy. This energy is used for plant growth and development, including the formation of larger and heavier ears [47]. In contrast, 1000 seed weight showed a low negative correlation with leaf area, ear length, and no. for seeds ear^{-1}, leaf dry weight, and stem dry weight, respectively. Competition may exist among the traits for assimilation. Greater vegetative growth (leaf area, leaf, and stem dry weight) may compete with reproductive growth (seed weight) for available assimilates, resulting in smaller seeds when vegetative traits are enhanced. Similar to the findings of Alaei et al. [48], plant height was negatively and weakly correlated with plant yield. A correlation was found between kernel ear^{-1} (0.658), No. Row ear^{-1} (0.985), ear diameter (0.785), and ear length (0.598) showed the strongest correlations with grain yield. Indeed, a highly significant and positive correlation between ear fresh weight and ear length, ear diameter, and number of seeds ear^{-1} was noted. These traits may be genetically linked, meaning that plants bred to have longer ears, larger diameters, and more seeds ear^{-1} also tend to have higher fresh ear weights. Higher biomass production is associated with increased grain yield in corn [49]. This relationship underscores the importance of plant vigour and overall biomass accumulation throughout the growing season.

4.6. The economic returns from fresh corn grown using different fertilizer managements

Both organic fertilizers (F2 and F3) significantly differed from the application of inorganic fertilizer (F4) in terms of ear yield. Specifically, the application of BSF mixed with inorganic fertilizer (F3) tended to provide an ear yield similar to that of inorganic fertilizer (F4) compared to vermicompost mixed with inorganic fertilizer (F2). The application of inorganic fertilizer (F4) and BSF mixed with inorganic fertilizer (F3) generated the highest net income among the three fresh corn cultivars. Our results indicated that the application of inorganic fertilizer (F4) resulted in a higher net return in purple waxy and sweet corn, followed by BSF mixed with inorganic fertilizer (F3). In contrast, the application of no fertilizer (F1) resulted in a higher net return in pink waxy corn, followed by inorganic fertilizer (F4), and BSF mixed with inorganic fertilizer (F3). However, ear yield did not differ significantly with fertilizer application. In contrast, Li et al. [29] reported that optimal fertilization practices significantly increased the fresh ear yield of waxy corn compared with no fertilizer. These results suggest that pink waxy corn may not be sensitive to fertilizer application, especially to inorganic fertilizers. With low initial capital investments, the application of BSF mixed with inorganic fertilizer (F3) is recommended for farmers. To promote sustainable intensification, smallholder farmers should produce organic fertilizers or recycle byproducts from farms to reduce production costs, minimise the use of inorganic fertilizers, improve yield quality, and contribute to a greener environment in the long term. In addition, farmers must add more organic fertilizer to produce fresh corn in an organic system. Furthermore, selecting an appropriate variety of fresh corn can help farmers reduce fertilizer costs.

4.7. The impact of the application of mixed organic and inorganic fertilizers on the environment

The conservation of soil quality using only organic resources requires a large number of applications. Organic fertilizers have low nutrient content and take a long time to release available minerals for crop growth. In contrast, inorganic fertilizers usually contain all the necessary nutrients and are readily accessible for crop growth in a short time. However, the application of inorganic fertilizers can affect the soil structure, leading to a decrease in organic matter, soil degradation, increased soil acidity, and environmental pollution [50]. Combining organic and inorganic fertilizers is an alternative, sustainable, and cost-effective approach for managing soil health, resulting in improved soil fertility and productivity without harming the environment [51]. Nevertheless, further field research should be conducted in different settings with multiple trials spanning at least three years to ensure wider applicability and reliability of the current research findings.

5. Conclusions

This study provides evidence that soil chemical parameters, such as pH, OM, EC, total N, available P, exchangeable K, Fe, total As, and Pb, can be improved using vermicompost and BSF mixed with inorganic fertilizers (F2 and F3). This led to the creation of favourable soil conditions for cultivating fresh corn. By reducing the use of inorganic fertilizer by 50 % according to GAP standards, the application of black soldier fly (BSF) mixed with inorganic fertilizer (F3) maintained the ear yield of the three fresh corn varieties, especially sweet corn. Pink waxy corn is an interesting option for cultivation under low soil fertility conditions because it generates more net income without the need for fertilizer application. Therefore, the use of BSF mixed with inorganic fertilizer (F3) is considered the best practice for farmers to maintain economic yield, protein and fibre content, net income, and to reduce the burden of environmental pollution. Further field research should be conducted in different settings to ensure wider applicability of the current research findings.

CRediT authorship contribution statement

Riri Dayang Sari Risman: Writing – original draft, Methodology, Data curation. **Chutima Nonkhonman:** Investigation. **Kiriya Sungthongwises:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Data availability statement

All data generated or analysed during this study are included in this research article and its supplementary information files. No data associated with this study have been deposited in any publicly available repository.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Riri Dayang Sari Risman reports article publishing charges, equipment, drugs, or supplies, statistical analysis, and writing assistance were provided by Khon Kaen University. Kiriya Sungthongwises reports a relationship with National Science Research and Innovation Fund (NSRF) that includes: funding grants. Kiriya Sungthongwises has patent The integration of vermicompost, black soldier fly, and inorganic fertilizers enhance plant growth and yield of fresh corn pending to Kiriya Sungthongwises. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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