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Black soldier fly frass compost improves soil fertility and tomato productivity in Ghana

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ABSTRACT

Organic fertilization using insect-derived compost offers an innovative pathway to sustainable and circular horticulture. This study evaluated the effect of Black Soldier Fly (BSF) frass compost on soil nutrient levels and tomato productivity under semi-arid tropical conditions in Ghana. A field experiment was conducted across two growing seasons in three locations within Ghana, using a randomized complete block design with seven fertilizer treatments, including control with no amendment, 200 kg ha^{-1} of NPK, 10 t ha^{-1} of commercial compost from Accra Compost and Recycling Plant (ACARP), 10 t ha^{-1} BSF compost, 5 t ha^{-1} ACARP compost + 100 kg ha^{-1} NPK, 5 t ha^{-1} BSF compost + 100 kg ha^{-1} NPK and 5 t ha^{-1} ACARP compost + 5 t ha^{-1} BSF compost. Results showed that BSF compost + NPK treatment achieved the highest yields (17 t ha^{-1}), outperforming other treatments. Sole BSF compost application increased soil organic carbon (+21 %), available nitrogen (+86 %), and available phosphorus (+33 %) relative to the control. BSF compost + NPK treatment improved nitrogen recovery efficiency (52 %) and reduced nitrogen losses by 24.6 %. Soil quality index analysis further revealed localized hotspots of improved soil fertility in BSF compost-treated plots. These findings position BSF compost as a climate-friendly input for integrated nutrient management and more sustainable vegetable production in semi-arid agroecosystems.

1. Introduction

The global challenge of achieving sustainable agriculture has grown more pressing, especially in developing countries, where declining soil fertility and limited access to financing for expensive mineral fertilizers hinder farming productivity (Bationo et al., 2018; Yeboah et al., 2024; Phiri et al., 2025). In Ghana, managing soil fertility sustainably remains a key strategy for ensuring food security and supporting economic growth (Ferreira et al., 2022). As environmental concerns increase and the need to promote circular economy principles rises, the search for recycled organic fertilizers that boost both ecological and agricultural sustainability has become increasingly vital.

Among the most promising innovations is the use of Black Soldier Fly (BSF) frass compost, a nutrient-rich byproduct derived from the larvae of *Hermetia illucens* L., which are known for their remarkable capacity to quickly biodegrade organic waste (Mertenat et al., 2019; Shelomi, 2020; Wu et al., 2020; Gärttling and Schulz, 2022; Mutuku et al., 2022; Wantulla et al., 2023; Kasima et al., 2025). These larvae can consume and convert a wide range of organic materials into protein-rich biomass and a frass-based compost, reducing waste volumes by as much as 80 % in as little as 7–14 days (Singh and Kumari, 2019; Salam et al., 2021). This transformation diverts large quantities of biodegradable waste from landfills, reduces associated methane emissions, and reintroduces nutrients into agricultural systems as a soil amendment, thus contributing to nutrient cycling and circular climate-smart agriculture (Bellezza Oddon et al., 2024).

Extensive studies have demonstrated that BSF frass compost provides a broad spectrum of nutrients essential for crop development. Typically,

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BSF frass contains total nitrogen in the range of 2.5–3.6 %, phosphorus (1.5–2.5 %), potassium (2–4 %), calcium (2.0–3.5 %), magnesium (0.5 %), and sulfur (0.3–0.8 %), with a substantial fraction of N and P in readily available forms for plant uptake (Anyega et al., 2021; Beesigamukama et al., 2020, 2021a; Boudabbous et al., 2023). It also supplies key micronutrients such as zinc, iron, manganese, and copper, alongside 20–30 % organic matter and a favorable carbon-to-nitrogen ratio (10–15:1), which stimulates microbial activity and nutrient cycling (Dzepe et al., 2022). Unlike many traditional composts that mineralize nutrients more slowly, BSF compost is noted for its relatively rapid nutrient release, driven by the BSF digestion processes, mineralization of chitin-rich residues and microbial processes that enhance soil enzymatic activities and solubilization of nutrients (Anyega et al., 2021). Comparisons with other organic amendments indicate that while conventional composts contribute more bulk organic matter, BSF frass often provides higher nutrient concentrations, resulting in faster plant response (Phiri et al., 2025). However, some studies have reported negative effects of insect frass at high application rates, including yield reductions and phytotoxicity linked to salinity, ammonium-N, and phenolic compounds (Song et al., 2021; Salomon et al., 2025)

Tomato (*Solanum lycopersicum* L.), a nutrient-intensive horticultural crop, presents a suitable model for studying the agronomic impacts of organic amendments like BSF compost (Amankwaa-Yeboah et al., 2023). In Ghana, tomato farmers frequently face challenges with nutrient-poor soils and limited access to fertilizers, which restrict productivity (Bergstrand et al., 2020; Amankwaa-Yeboah et al., 2023). Prior studies suggest that organic amendments can affect nutrient dynamics in tomato tissues, influencing concentrations of nitrogen, phosphorus, potassium and trace elements such as zinc and manganese (Dzepe et al., 2022; Chavez et al., 2023; Arabzadeh et al., 2024; Awad et al., 2024; Siddiqui et al., 2024). However, in the Ghanaian context, there remains a limited empirical understanding of how BSF compost influences soil fertility and nutrient uptake of tomato, which is the most important vegetable crop in Ghana. and plant tissue composition.

To address this knowledge gap, the present study is guided by the central research question: How does the application of BSF compost affect soil chemical properties and nutrient uptake in tomato plants under semi-arid conditions of Ghana? This question is grounded in the hypothesis that BSF compost would significantly improve soil nutrient levels and increase nutrient uptake efficiency in tomato plants compared to unamended soil and conventional fertilization alone. Specifically, the objectives of this study are to: (i) assess the effects of sole and combined applications of BSF compost, mineral fertilizer, and traditional compost on soil nutrient dynamics and to (ii) determine the influence of these treatments on nutrient uptake and tomato yield. The practicality of this study lies in its integration of circular bioresource use with agronomic recommendations in a tropical field context. While BSF compost has been explored in controlled environments or temperate conditions, this study is among the first to rigorously evaluate its effects on soil chemistry and tomato nutrient use efficiency under open-field, real-world conditions of West African agroecological zone.

2. Materials and methods

2.1. Study area

Field experiments were conducted under semi-arid conditions in two seasons (Nov 2022 - Mar 2023 and Nov 2023 - Mar 2024) at Bagri, Babile, and Naburanye in Lawra District, Upper West Region, Ghana. The district has a unimodal rainfall pattern (840 mm - 1400 mm annually) with a dry season from November to April, influenced by harmattan winds. During the experimental period, climatic data were recorded onsite using data loggers. Across the two seasons, maximum temperatures ranged from 44°C to 50°C, while minimum temperatures dropped as low as 7.5°C. Relative humidity varied widely, from as low as 8.5–100 %, with seasonal averages around 44.5 % and 51.8 % (Table 1). Though moderately fertile, the region's ferric and lateritic soils are shallow and prone to degradation.

2.2. Sources of nutrient amendments

The study used three fertilizers: two organic types (BSF frass compost and commercial ACARP compost) and an inorganic fertilizer (NPK). The BSF frass compost was prepared at the Biotechnology and Nuclear Agricultural Research Institute of Ghana Atomic Energy Commission in Accra, Ghana, and produced by rearing Black Soldier Fly larvae on decomposed organic waste, including fruit and vegetable residues. The organic waste was pre-composted for 7 days before larval feeding to reduce pathogen load, stabilize the substrate and enhance nutrient availability. This step was necessary to ensure biosecurity, minimize harmful microbial activity, and create a more homogeneous and digestible feed substrate for the BSF larvae, especially when using mixed fruit and vegetable residues collected from open markets (Meneguz et al., 2018). Following standard protocols, the waste was pre-composted to enhance nutrients and ensure safety. The larvae were fed on the substrate under optimal conditions (27–30°C, 60–70 % humidity, proper aeration), and the frass was collected after harvesting the larvae, dried, and sieved into a fine fertilizer (Beesigamukama et al., 2021b; Siddiqui et al., 2022). The frass was further composted in an open field using the heap method, with 1 m tall and 4 m long heaps hydrated to 55–65 % moisture and covered with polythene sheets to retain heat and humidity. Weekly turning ensured even decomposition, while compost maturity was tracked through C/N ratio, pH, and electrical conductivity. A stable compost product was ready in five weeks. ACARP, the commercial organic fertilizer, was sourced from Accra Compost and Recycling and derived from the controlled decomposition of organic municipal waste, such as food scraps and garden trimmings. NPK (15:15:15) compound fertilizer was procured from an agro-input dealer in Wa, Upper West Region, Ghana. The pre-experiment soil characteristics are detailed in Table 2.

Table 1
Summary of Temperature, Relative Humidity, and Dew Point in Babile and Bagri/Naburnye for the Years 2023 and 2024.

Year		Babile			Bagri/Naburnye		
		Temperature (°C)	Relative humidity (%)	Dew point (°C)	Temperature (°C)	Relative humidity (%)	Dew point (°C)
2023	Max	48	100	29.6	49.5	100	32
	Average	25.5	51.8	11.1	25.9	51.2	11.4
	Min	7.5	8.5	0	7.5	10	7.5
	Std	10.7	30.3	4.4	10.9	29.6	10.9
2024	Max	50	99.5	21.4	44	95	16.9
	Average	26.2	44.5	9	21.9	13.5	11.5
	Min	8.5	9	–0.7	12.5	61.6	7.1
	Std	11.4	29.7	3.3	9.9	27.1	1.2

Note: Temperature (°C): Air temperature recorded in degrees Celsius. Relative Humidity (%RH): Percentage of water vapor in the air relative to the maximum amount the air can hold at that temperature. Dew Point (°C): The temperature at which air becomes saturated with moisture and dew forms. Max: Maximum recorded value during the observation period. Average: Mean value across the season. Min: Minimum recorded value during the observation period.

Table 2
Physicochemical properties of experimental soil and organic fertilizers Used in the study.

Experimental Soil													
Parameter	pH H_20 (1:2.5)	OC %	Total N	Available P Mg/kg	NO_3^-	NH_4^+	OM %	Ca^{2+} Meg/100 g	Mg^{2+}	K^+ %	Sand	Silt	Clay
Test Value	6.1	0.77	0.15	29.4	6.82	3.23	1.33				75.28	8.08	16.63
Organic Fertilizers													
Parameters	pH H_20 (1:2.5)	OC %	Total N	Available P Mg/kg	NO_3^-	NH_4^+	OM %	Ca^{2+} Meg/100 g	Mg^{2+}	K^+ %	Sand	Silt	Clay
BSF Frass	7.72	1.33	3.6	90.3		3.9	90.3	0.39	0.15	1.8			
ACARP	7.42	2.65	2.5	33.74		2.56	33.74	0.34	0.21	1.1			

2.3. Experimental design and agronomic management

A randomized complete block design of seven soil nutrient management treatments with three replications was established (21 units). The experimental plots had dimensions of 1 m x 4.8 m^2 per unit plot and were designed with a 2-meter border around each plot. The total area used was 276 m^2 per experimental field and plots were separated by 1-meter alleys to prevent treatment overlap. The experiment was conducted with the Padmar 108 F1 tomato variety, a high-performing hybrid tomato resistant to Fusarium wilt and Tomato Mosaic Virus, yielding 20–25 t ha^{-1}. Experimental fields were cleared and plowed to a depth of 0.20 m. The seven treatments included control with no soil amendment (T1), 200 kg ha^{-1} of NPK (T2), 10 t ha-1 of ACARP compost (T3), 10 t ha^{-1} BSF compost (T4), 5 t ha^{-1} ACARP + 100 kg ha^{-1} NPK (T5), 5 t ha^{-1} BSF compost + 100 kg ha^{-1} of NPK (T6) and 5 t ha^{-1} of ACARP + 5 t ha^{-1} of BSF compost (T7). The inherently low fertility of the study area's soils, characterized by low organic carbon, total nitrogen, and phosphorus levels, presents significant constraints for tomato growth (Buah et al., 2017). To address these limitations, BSF compost (10 t ha^{-1} and 5 t ha^{-1}) and ACARP compost (10 h^{-1} and 5 t ha^{-1}) were applied to enhance organic matter, nitrogen content, microbial activity, and phosphorus availability, as seen in previous studies where organic amendments improved soil nutrient retention and plant performance (Beesigamukama et al., 2021a; Dzepe et al., 2022). The split application of NPK (200 kg ha^{-1} and 100 kg ha^{-1}) ensures an immediate supply of nitrogen and potassium, reducing losses and improving uptake, a strategy consistent with nutrient management recommendations for sandy and lateritic soils (Alori et al., 2023). The total N input per treatment ranged from 200 to 360 kg N ha^{-1}. Five out of the seven treatments, which received 5 t ha^{-1} and 10 t ha^{-1} of the BSF compost and the ACARP compost, had the organic fertilizers incorporated 14 days before transplanting the seedlings into the growing beds. Four-week-old seedlings were transplanted with a spacing of 60 cm between rows and 40 cm within rows. Each row had 12 plants and a total of 24 plants per plot. The basal application of the NPK 15:15:15 inorganic fertilizer was made on the 14th day after the seedlings were transplanted, and the top dressing was applied after the sixth week.

2.4. Sample collection, preparation and analysis

Plant and soil samples were collected after harvest, following standard protocols (Carter and Gregorich, 2007). Five representative plants per treatment plot were randomly selected based on uniformity in height and vigor. Leaves, stems, and fruits were separated for nutrient analysis. Plant samples (stems and leaves) were oven-dried at 65°C to a constant weight and then ground separately for analysis. Soil samples were collected at a depth of 0–30 cm using an auger, with five subsamples per plot combined to form a composite sample, ensuring spatial representation. Soil samples were air-dried, ground, and sieved through a 2-mm mesh before chemical analysis (Jones, 2001). Soil organic carbon (OC) was analyzed using the Walkley-Black method. Total nitrogen (N) was determined using the Kjeldahl method, whilst available phosphorus (P) was analyzed using the Bray-1 method. Exchangeable potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) were extracted using 1 M ammonium acetate (pH 7.0) and quantified using atomic absorption spectrophotometry (AAS). Soil pH was measured in a 1:2.5 soil-to-water suspension using a pH meter. Plant tissue analysis of stems and leaves followed wet acid digestion procedures. Total nitrogen content was determined using the Kjeldahl method, while phosphorus, potassium, magnesium, and calcium were analyzed using spectrophotometry and flame photometry, respectively. Yield was measured by weighing defect-free fruits and standardized by dividing the total fruit weight by the area of the plot. All analyses were conducted at the soil science laboratory of the Savanna Agricultural Research of the Council for Scientific and Industrial Research, Ghana.

2.5. Statistical analysis and modeling

2.5.1. Nitrogen use efficiency indices

The nitrogen use efficiency indices included Agronomic Nitrogen Use Efficiency (ANUE), Agrophysiological Nitrogen Efficiency (APE), Nitrogen Recovery Efficiency (NRE), and Nitrogen Loss (Nloss). ANUE measures the yield increase per unit of nitrogen applied (Govindasamy et al., 2023), APE evaluates the physiological response of the crop to nitrogen uptake (Zhigang Wang et al., 2022), NRE indicates the percentage of applied nitrogen recovered by the crop and nitrogen loss estimates the portion of applied nitrogen lost to the environment (Anas et al., 2020; Zhigang Wang et al., 2022). The following formulae were used:

$$ANUE = \frac{Y_f - Y_0}{N_a} \tag{1}$$

$$APE = \frac{Y_f - Y_0}{N_U} \tag{2}$$

$$NRE = \frac{N_u - N_0}{N_a \times 100} \tag{3}$$

$$Nloss = N_a - N_u \tag{4}$$

where Y_f and Y_0 represent yields with and without fertilizer, N_a is the applied nitrogen, Nu is the nitrogen uptake with fertilizer, and N_0 is the nitrogen uptake without fertilizer.

2.5.2. Linear mixed effect (LMM) and linear regression models

To analyze treatment effects while accounting for temporal and spatial variations, LMMs were applied using the R *lme4* package (Bates et al., 2015) (Eq. 5). The relationship between soil fertility and time (year) was analyzed using linear regression (Eq. 6).

$$Y_{ij} = \beta_0 + \beta_1 X_{ij} + u_i + \epsilon_{ij} \tag{5}$$

$$Y = \beta_0 + \beta_1 x + \epsilon_y \tag{6}$$

where Y_{ij} is the response variable for treatment i at time j, β_0 is the fixed intercept, $\beta_1 X_{ij}$ represents the fixed effect of the predictor, and u_i is the random effect of treatment. ϵ_{ij} is the residual error, y represents the predicted soil fertility score, x is the year, β_1 is the slope, ϵy is the error term.

2.5.3. Autoregressive integrated moving average (ARIMA)

The analysis employed an Autoregressive Integrated Moving Average (ARIMA) model for time series forecasting of soil fertility parameters with the model expressed as ARIMA (p,d,q), where p is the order of the autoregressive component, d is the degree of differencing required for stationarity and q is the order of the moving average component (Schaffer et al., 2021). The ARIMA model incorporated the following input parameters: phosphorus content, potassium content, organic carbon content, and nitrogen content. Separate ARIMA models were fitted for T4, T5, and T6 using the Auto-Correlation function (ACF), Partial Autocorrelation Function (PACF), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC) for parameter selection. The Pearson correlation identified phosphorus as the strongest predictor ($r = 0.75$) of soil fertility. ARIMA models (2023–2024) were estimated via maximum likelihood, with residual diagnostics ensuring adequacy. A weighted formula, based on correlation coefficients, integrates nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC) to compute the overall fertility score, as shown in Eq. 9. Fertility scores were forecasted for 2035 with 95 % confidence intervals, and treatments were compared. Models were validated using leave-one-out cross-validation, Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Ljung-Box tests.

$$FS = w_P.P + w_K.K + w_{OC}.OC + w_N.N \tag{7}$$

Where FS is the soil fertility score; w_P, w_k, w_{OC}, and w_N are the weights assigned to each parameter, proportional to their respective correlation coefficients. P, K, OC, and N are the normalized values of phosphorus, potassium, organic carbon, and nitrogen.

2.5.4. Soil quality index (SQI) analysis

SQI is computed as a weighted sum of normalized soil parameters (Eq. 10) (Chen et al., 2024). Parameters are standardized using mean and standard deviation (Eq. 11). SQI is refined using PCA-derived weights for key soil properties (P, K, N, Mg, OC, pH, Ca) (Eq. 12). Moran's I assesses the spatial dependence of SQI values (Eqn 13).

$$SQI = \sum_{i=1}^{n} w_i.z_i \tag{8}$$

$$z_i = \frac{x_i - m}{\sigma} \tag{9}$$

$$SQI = 0.288 \quad . \quad z_P + 0.236.z_K + 0.137.z_N + 0.133.z_{Mg} + 0.111.z_{OC} + 0.053.z_{pH} + 0.043.z_{Ca} \tag{10}$$

$$I = \frac{n}{\sum_i \sum_j w_{ij}} \quad . \quad \frac{\sum_i \sum_j w_{ij}(z_i - m)(z_j - m)}{\sum_i (z_i - m)^2} \tag{11}$$

Where w_i is the weight assigned to soil parameter i, z_i is the normalized value of soil parameter I, and n is the total number of soil parameters considered. x_i is the measured value of the soil parameter i. m is the mean value of the soil parameter across all samples. σ is the standard deviation of the soil parameter. Z_P, Z_K, Z_N, Z_{Mg}, Z_{OC}, Z_{pH}, and Z_{Ca} are the normalized values for phosphorus, potassium, nitrogen, magnesium, organic carbon, pH, and calcium, respectively. n is the number of spatial units, w_{ij} is the spatial weight between locations i and j, z_i is the SQI value at location i.

2.5.5. Carbon stock estimation

Soil carbon stock was calculated using the following (Tadiello et al., 2022):

$$CS = OC \times BD \times D \times CF \tag{12}$$

Where CS = Carbon stock (tons per hectare). OC = organic carbon content (%). BD = bulk density, which was measured to be 1.3 g/cm^3 . D = soil depth (30 cm). CF = conversion factor (100, to express in t/ha). The assumption was that the bulk density was constant at 1.3 g/cm^3 . The sampling depth was standardized to 30 cm. No corrections were made for rock fragments or soil texture.

2.5.6. Data analysis

All data analyses were performed using R statistical software version 4.3.2. The agricolae package was utilized for post hoc mean separation using Tukey's Honest Significant Difference (HSD) test, while data visualization was performed using the ggplot2 package.

3. Results

3.1. Effect of nutrient amendment on soil chemical properties

The analysis of soil chemical properties in 2023 and 2024 revealed significant nutrient variations across treatments (Table 3). Nitrate, ammonium, and organic carbon levels increased over two seasons, with T6 showing the highest nitrate (54.05 mg kg^{-1}) and ammonium (8.56 mg kg^{-1}) in 2024, while T4 led in organic carbon (1.52 %). Calcium, potassium, phosphorus, and magnesium also varied, with T6 maintaining the highest calcium and phosphorus, and T4 recording peak magnesium levels. Total nitrogen fluctuated, with T4 highest in 2023 (0.50 %) and T2 in 2024 (0.94 %). Soil pH showed slight variation but no significant treatment effect. Overall, BSF frass compost, particularly in T4 and T6, enhanced key soil fertility parameters over time. Nutrient levels varied significantly between flowering and harvest stages in both years. Nutrient concentrations in soil varied notably between the flowering and harvesting stages across both years. In 2023, nitrate levels were higher at flowering (3.49–46.71 mg/kg) than at harvest (2.54–44.83 mg/kg), with T5 showing a 53.6 % decline. Similar patterns were observed in 2024, with T3 recording a 55.2 % drop. Organic carbon and nitrogen showed moderate reductions across stages, with slightly greater decreases in 2024. Phosphorus availability consistently declined from flowering to harvest, with T6 and overall treatments showing average decreases of 13.4 % (2023) and 11.8 % (2024). Ammonium also declined across stages in both years by approximately 14–16 %. Among base cations, potassium exhibited the highest stage-dependent decline, with reductions of 18.3 % in 2023 and 16.9 % in 2024. Significant stage × treatment interactions ($p < 0.05$) were observed, especially for nitrate and phosphorus, with nitrate showing the highest variability.

3.1.1. Soil fertility prediction patterns

Based on a comprehensive analysis of soil fertility treatments from 2023 to 2024 and projections to 2035, our findings reveal significant patterns in soil fertility dynamics (Fig. 1). The strongest correlation with the overall fertility score was found with phosphorus content, demonstrating a high correlation coefficient of 0.7. Potassium demonstrated a moderate relationship with a correlation of 0.48, while organic carbon and nitrogen showed correlations of 0.386 and 0.286, respectively. Treatment T6 emerged as the most promising intervention, with projections indicating a potential fertility score of 22.32 by 2035 (95 % CI: 14.97–22.32). This represents a substantial improvement from baseline conditions, with a relatively stable confidence range of ±3.67 units. T6 consistently maintains higher fertility scores with lower variability compared to other treatments. In contrast, T4 showed declining effectiveness over time, with projected fertility scores dropping to 2.79 (95 % CI: 2.79–10.44) by 2035. T5 presents an intermediate outcome, with projected scores of 12.88 (95 % CI: 8.22–12.88) and the most stable confidence range (±2.33) among all treatments.

3.1.2. Soil quality index analysis as affected by different fertilizer applications

Soil quality index (SQI) analysis revealed strong spatial clustering, with Moran's index increasing from 0.813 (2023) to 0.904 (2024,

Table 3
Soil chemical properties following application of different fertilizers, including NPK, traditional compost, and BSF frass to tomato crops in Ghana in 2023 and 2024.

Parameter	Year	T1	T2	T3	T4	T5	T6	T7	p-v
Ca^{2+}(meg/ 100 g)	2023	3.67 ± 0.68 b	4.42 ± 2.2 ab	4.42 ± 0.94 ab	4.05 ± 1.24 ab	6.35 ± 0.42 b	6.95 ± 1.91 a	3.88 ± 1.12 ab	0.013
	2024	3.79 ± 0.68 a	3.86 ± 1.53 ab	4.8 ± 0.73 ab	6.91 ± 1.46 bc	6.9 ± 0.67 bc	8.19 ± 1.14c	4.65 ± 1.48c	0.000
K^{+}(meg/ 100 g)	2023	0.09 ± 0.07c	1.44 ± 0.19 a	0.66 ± 0.16 bc	1.14 ± 0.24 abd	1.33 ± 0.39 ad	1.14 ± 0.14 abd	0.82 ± 0.40 bd	0.000
	2024	0.26 ± 0.28 a	1.33 ± 0.42 a	0.86 ± 0.07 ab	1.91 ± 0.42 ab	1.48 ± 0.46 bc	1.76 ± 0.14 bc	0.93 ± 0.36c	0.000
P (%)	2023	13.56 ± 9.66 b	41.78 ± 13.92 ab	22.10 ± 13.77 b	60.85 ± 59.99 ab	47.61 ± 27.83 ab	92.42 ± 22.92 a	31.21 ± 13.56 ab	0.014
	2024	13.83 ± 10.5 a	46.85 ± 9.91 ab	26.48 ± 13.64 b	54.59 ± 29.9 b	48.97 ± 24.45 b	93.62 ± 16.99 b	34.26 ± 14.64 b	0.000
Mg^{2+}(meg/ 100 g)	2023	0.77 ± 0.44 a	0.94 ± 0.58 a	0.75 ± 0.32 a	1.52 ± 0.36 a	0.53 ± 0.55 a	1.44 ± 0.51 a	0.99 ± 0.32 a	0.047
	2024	0.94 ± 0.7 a	0.78 ± 0.31 a	1.02 ± 0.32 ab	2.14 ± 0.45 ab	0.87 ± 0.67 b	2.12 ± 0.45 b	1.27 ± 0.36 b	0.001
NO_3^-(mg/ kg)	2023	3.30 ± 0.53 a	32.50 ± 24.78 a	14.37 ± 16.30 a	14.49 ± 11.88 a	35.65 ± 20.52 a	43.38 ± 30.16 a	12.43 ± 9.24 a	0.055
	2024	4.45 ± 0.85 a	38.62 ± 25.19 ab	22.67 ± 14.06 ab	24.3 ± 12.52 ab	39.89 ± 17.75 ab	54.05 ± 28.5 ab	21.02 ± 12.32 b	0.021
N (%)	2023	0.19 ± 0.09c	0.42 ± 0.04 ab	0.25 ± 0.13 bc	0.50 ± 0.13 a	0.18 ± 0.10c	0.31 ± 0.13 abc	0.17 ± 0.03c	0.000
	2024	0.27 ± 0.09 a	0.94 ± 0.54 ab	0.38 ± 0.13 ab	0.74 ± 0.1 ab	0.43 ± 0.05 ab	0.78 ± 0.38 ab	0.55 ± 0.22 b	0.021
NH_4^+(mg/ kg)	2023	3.50 ± 2.18 a	5.86 ± 0.71 a	2.58 ± 0.53 a	4.59 ± 1.24 a	4.96 ± 2.02 a	5.73 ± 2.00 a	2.95 ± 0.52 a	0.023
	2024	3.62 ± 2.08 a	6.24 ± 0.56 ab	3.04 ± 0.84 abc	5.99 ± 2.09 abc	7.37 ± 3.07 abc	8.56 ± 1.52 bc	5.8 ± 0.83c	0.003
OC (%)	2023	0.44 ± 0.11c	0.82 ± 0.14 abc	0.66 ± 0.26 bc	1.25 ± 0.29 a	0.93 ± 0.28 abc	1.03 ± 0.27 ab	0.91 ± 0.31 abc	0.005
	2024	0.42 ± 0.13 a	0.67 ± 0.25 ab	0.69 ± 0.22 ab	1.52 ± 0.72 ab	0.99 ± 0.38 ab	1.22 ± 0.38 ab	0.92 ± 0.38 b	0.013
pH	2023	5.62 ± 1.23 a	5.38 ± 0.49 a	6.56 ± 0.33 a	6.20 ± 0.24 a	5.41 ± 0.44 a	5.35 ± 0.46 a	6.43 ± 0.34 a	0.022
	2024	6.29 ± 1.16 a	5.16 ± 0.41 a	6.72 ± 0.34 a	6.53 ± 0.42 a	6.11 ± 0.78 a	6.73 ± 0.35 a	6.58 ± 1 a	0.062

Note: The table shows the mean ± standard error of soil nutrient parameters measured in 2023 and 2024 under different fertilizer treatments (T1–T7). Superscript letters (a, b, c) indicate significant differences between treatments within each year based on post hoc comparison test at $p < 0.05$.*** $p \leq 0.001$ (highly significant) ** $p \leq 0.01$ (very significant) * $p \leq 0.05$ (significant) ns: not significant ($p > 0.05$). Control (T1), 200 kg ha^{-1} of NPK (T2), 10 t ha^{-1} of ACARP compost (T3), 10 t ha^{-1} BSF compost (T4), 5 t ha^{-1} ACARP and 100 t ha^{-1} NPK combined (T5), 5 t ha^{-1} BSF frass compost with 100 kg ha^{-1} NPK (T6) and 5 t ha^{-1} ACARP with 5 t ha^{-1} BSF compost (T7). Parameters include: Nitrate (NO_3^-), Ammonium (NH_4^+), Nitrogen (N), Potassium (K+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Phosphorus (P), Organic Carbon (OC) and pH (Soil pH in 1:2.5 H_2O solution

$p < 0.001$), indicating intensified autocorrelation (Fig. 2). Hotspot analysis identified T6 (+19.8 %) and T4 (+18.2 %) as the most effective treatments in terms of improving the soil quality index ($p < 0.05$). Spatial spillover effects were evident (Moran's I = 0.590), reinforcing treatment impact. PCA ranked phosphorus (28.8 %) and potassium (23.6 %) as the top contributors to SQI, followed by nitrogen (13.7 %), magnesium (13.3 %), and organic carbon (11.1 %). In contrast, pH (5.3 %) and calcium (4.3 %) had the least influence.

3.2. *Effect of various fertilizer applications on tomato yield and nutrient uptake*

Yield comparisons over two years showed clear treatment effects. In 2023, treatment effects were also significant ($p < 0.05$), with T6 leading but with greater variability (Table 4). The yield spread in 2023 was wider. In 2024, the treatment impact was highly significant ($p < 0.001$), with T6 yielding the highest response, followed by T4 and T2. Nitrogen concentrations in the tomato stems showed significant treatment effects in both years (Table 4). T6 had the highest nitrogen in 2023 (1.14 %), while T2 led in 2024 (1.38 %). Organic carbon was highest in T6 across the years, with notable increases in T4 and T6. Phosphorus (P) in stems peaked in T4 in both years (19.30 mg/kg in 2023 and 22 mg/kg in 2024). In tomato leaves, nitrogen followed a similar trend, with T6 having the highest levels in 2023 (1.40 %) but declining in 2024 when T1 had the lowest levels (0.26 %). Organic carbon also increased, with T4 leading at 58.22 % in 2024. Leaf phosphorus levels were highest in T4 and T6 in 2023, while T7 experienced a notable increase in 2024 (16.93 mg/kg).

3.2.1. *Nutrient use efficiencies and correlations between soil chemical properties*

The NUE analysis showed significant treatment differences in ANUE, APE, NRE, and nitrogen loss (Table 5). In 2023, T2 had the highest ANUE, T3 the highest APE, and T6 the highest NRE, while T4 experienced the most significant nitrogen loss. By 2024, ANUE and APE increased, with T6 and T3 leading, respectively, while nitrogen loss peaked in T3.

3.2.2. *Multivariate analysis of soil, stem and leaf chemical properties as affected by different fertilizer applications*

The principal component analyses (PCA) for 2023 and 2024 revealed consistent nutrient patterns shaped by the fertilizer treatments (Fig. 3). In both years, PC1 (explaining ~31 % of variance) represented a soil fertility gradient dominated by exchangeable cations (Ca^{2+}, Mg^{2+}, K^+), nitrate, and total N, while PC2 (~16–17 %) captured a trade-off between soil pH and NH_4^+ versus phosphorus allocation to leaf and stem tissues. Treatments combining BSF compost with NPK (T6) and ACARP with NPK (T5) consistently clustered on the nutrient-rich end of PC1. Sole BSF compost (T4) improved soil nutrients moderately, while dual compost (T7) plots shifted positively along PC1 over time. Control plots (T1) remained nutrient-poor but showed higher relative tissue P.

3.3. *Nutrient uptake distribution and carbon sequestration metrics as affected by different fertilizer applications*

The data showed significant variations in nutrient allocation among plant parts, with treatment-specific differences (Fig. 4). Phosphorus distribution varied notably, with T2 showing the largest disparity where stems accumulated significantly more phosphorus than leaves (4.78 mg/ml difference. Treatment T6 was unique in showing slightly higher nitrogen content in leaves compared to stems (+0.079 %), while all other treatments maintained higher nitrogen concentrations in stem tissues. Organic carbon showed the highest variability among all nutrients, with a variance of 10.82 in differential uptake. Treatment T3 displayed the most pronounced difference, with stems containing 10.35 % more organic carbon than leaves.

Organic carbon had the highest variability, with T3 showing the greatest difference stems (10.35 %) than leaves. T4 excelled in carbon sequestration, increasing soil organic carbon by 0.27 % and carbon stock by 10.60 t ha^{-1}. T2 and T6 led in total nitrogen increases (0.52 % and 0.48 %, respectively), with T6 also showing the highest nitrate (10.67 mg kg^{-1}) and ammonium (2.83 mg kg^{-1}) gains. T6 further increased organic carbon by 0.19 % and carbon stock by 7.6 t ha^{-1}, while T1 and T2 showed slight declines in both.

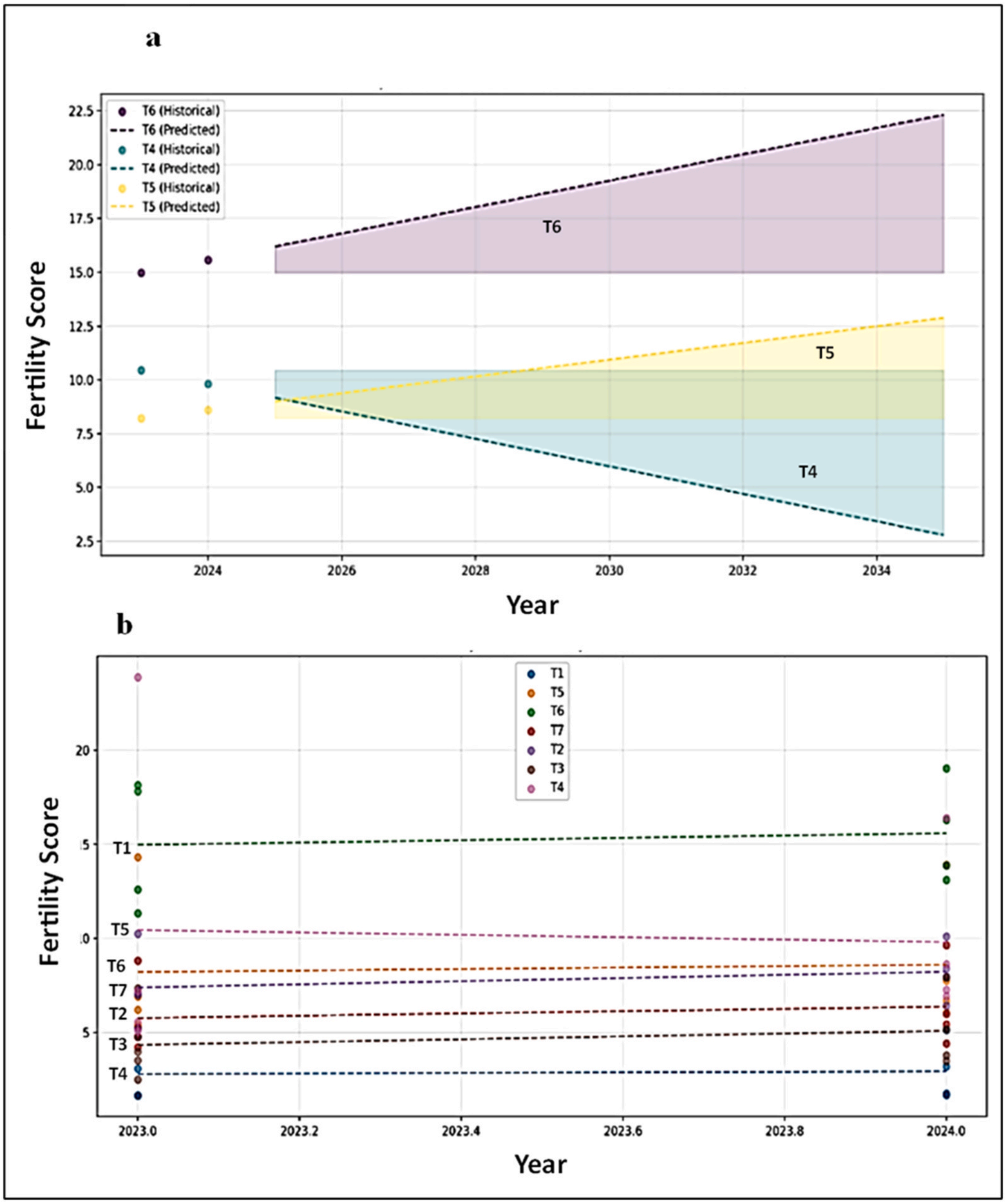

Fig. 1. Temporal Trends and Predictive Modeling of Soil Fertility Scores under Different Fertilizer Treatments. (a) Historical and predicted fertility score trajectories from 2023 to 2035 under selected fertilizer treatments (T4, T5, and T6) based on observed experimental data and linear model projections. Shaded regions represent model confidence intervals. T6 shows a continuous upward trend, indicating sustainable fertility improvement, while T4 shows a projected decline. (b) Distribution of annual fertility scores under all seven treatments (T1–T7) across the 2023–2024 cropping seasons. Each point represents a replicate measurement, and dashed lines indicate mean fertility scores for each treatment across years. Fertility score is a composite index derived from standardized soil chemical parameters. Predictive trends were modeled using linear regression. Error terms and standard deviations are incorporated in the predictive bands (panel a) and distribution spread (panel b). Control (T1), 200 kg ha-1 of NPK (T2), 10 t ha-1 of ACARP compost (T3), 10 t ha-1 BSF frass compost (T4), 5 t ha-1 ACARP and 100 t ha-1 NPK combined (T5), 5 t ha-1 BSF frass compost with 100 kg ha-1 NPK (T6) and 5 t ha-1 ACARP with 5 t ha-1 BSF frass compost (T7).

4. Discussion

This study highlighted that improved crop performance was primarily due to the consistent enhancement of key soil chemical properties through the application of BSF compost. Specifically, sole BSF compost and BSF compost + NPK significantly boosted soil organic carbon, nitrogen, phosphorus, base cations and yield levels over two growing seasons. BSF + NPK consistently outperformed sole BSF compost and mineral fertilizer alone, indicating that the combined strategy was the most effective in enhancing soil fertility. These results align with previous research, which found an increase in organic matter attributed to insect frass owing to its stable carbon compounds (Beesigamukama et al., 2020; Manirakiza and Şeker, 2020; Zaato et al., 2025). The improvements observed can be attributed to the nutrient release kinetics of BSF frass, which contains a relatively high fraction of readily mineralizable nitrogen and phosphorus, released gradually, thereby synchronizing more closely with crop demand. This contrasts with mineral fertilizer inputs that release nutrients rapidly but are prone to leaching or volatilization losses (Zaato et al., 2025).

Nitrogen and phosphorus dynamics further illustrate the effectiveness of BSF compost as a soil amendment in tropical environments. The observed nitrogen enhancement under BSF compost treatments aligns with Salomon et al. (2025), who attributed such increases to the high nitrogen content of BSF frass. Additionally, the dramatic rise in

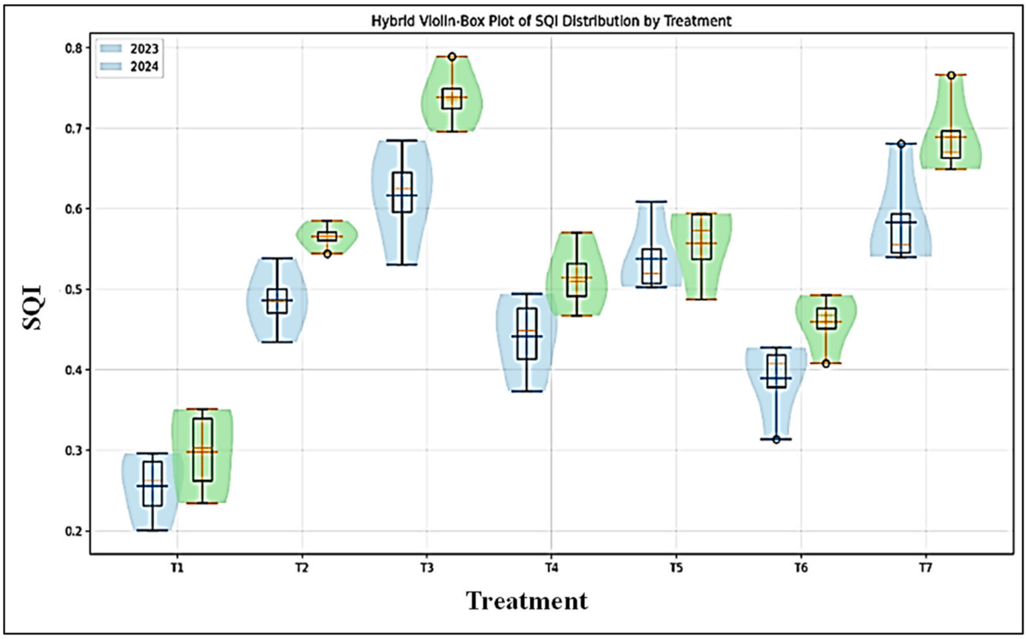

Fig. 2. Soil Quality Index (SQI) Distribution across Fertilizer Treatments in 2023 and 2024. Hybrid violin-box plot showing the distribution and variability of Soil Quality Index (SQI) values across seven fertilizer treatments (T1–T7) over two cropping seasons. The blue violins represent data from 2023, while green violins represent 2024. Each violin illustrates the full distribution of SQI values, with overlaid box plots indicating the interquartile range (IQR), median (horizontal line), and whiskers showing variability outside the upper and lower quartiles. SQI was calculated from normalized values of key soil parameters, including pH, total nitrogen, organic carbon, and available phosphorus. Higher SQI values reflect better soil health and functionality. Notably, T3 and T7 exhibited consistently higher SQI scores in both years, indicating superior soil quality under these treatments. Control (T1), 200 kg ha^{-1} of NPK (T2), 10 t ha^{-1} of ACARP compost (T3), 10 t ha^{-1} BSF frass compost (T4), 5 t ha^{-1} ACARP and 100 t ha^{-1} NPK combined (T5), 5 t ha^{-1} BSF frass compost with 100 kg ha^{-1} NPK (T6) and 5 t ha^{-1} ACARP with 5 t ha^{-1} BSF frass compost (T7).

Table 4
Effect of fertilizer treatments on tomato yield and nutrient distribution in stems and leaves for 2023 and 2024 growing seasons.

Parameter	Year	T1	T2	T3	T4	T5	T6	T7	p-v
Yield	2023	9.3 b	16.05 a	15.31 a	14.89 a	13.28 ab	16.87 a	15.73 a	0.017
	2024	5.57 e	12.51 bc	9.08 d	15.24 ab	10.14 cd	16.24 a	10.96 a	0.001
Stems									
N (%)	2023	0.62 ± 0.13 b	1.13 ± 0.21 a	0.92 ± 0.13 ab	0.85 ± 0.12 ab	1.02 ± 0.12 a	1.14 ± 0.27 a	0.98 ± 0.27 a	0.0006
	2024	0.37 ± 0.2 a	1.38 ± 0.17 b	0.69 ± 0.16 b	0.79 ± 0.16 b	0.98 ± 0.3 b	0.9 ± 0.16 bc	0.99 ± 0.21c	0.0001
OC (%)	2023	35.68 ± 5.18c	43.94 ± 2.43 ab	37.23 ± 5.49 bc	42.38 ± 3.92 abc	41.79 ± 2.15 abc	44.65 ± 4.39 a	43.94 ± 2.82 ab	0.0012
	2024	34.02 ± 3.94 a	40.47 ± 1.65 a	43 ± 5.41 b	59.17 ± 4.06 bc	46.55 ± 1.01 bc	55.8 ± 3.79c	48.02 ± 2.57 d	0.0001
P (%)	2023	10.72 ± 3.30 ab	8.17 ± 3.84 b	9.60 ± 2.39 b	19.30 ± 8.43 a	9.16 ± 5.01 b	16.42 ± 5.03 ab	16.21 ± 4.58 ab	0.0014
	2024	7.24 ± 1.3 a	18.13 ± 1.48 ab	11.25 ± 2.92 ab	22 ± 4.15 ab	12.98 ± 1.8 bc	18.78 ± 3.97c	18.28 ± 5.58c	0.0001
Leaves									
N (%)	2023	0.48 ± 0.17 d	1.21 ± 0.28 ab	0.75 ± 0.11 cd	1.02 ± 0.16 abc	1.14 ± 0.29 abc	1.40 ± 0.35 a	0.97 ± 0.11 bc	0.0001
	2024	0.26 ± 0.15 a	1.12 ± 0.26 ab	0.44 ± 0.17 ab	0.72 ± 0.14 abc	0.76 ± 0.21 bc	0.98 ± 0.23 cd	0.87 ± 0.19 d	0.0001
OC (%)	2023	30.36 ± 6.32c	33.57 ± 4.53 bc	38.19 ± 5.79 abc	40.27 ± 7.22 ab	43.30 ± 3.20 ab	44.03 ± 5.49 a	38.42 ± 4.91 abc	0.001
	2024	31.48 ± 5.83 a	36.53 ± 3.27 a	32.65 ± 5.35 b	58.22 ± 5.29 bc	42.85 ± 3.03 cd	55.48 ± 3.66 d	44.97 ± 4.36 d	0.0001
P (%)	2023	9.90 ± 1.26 b	11.83 ± 2.45 b	12.16 ± 3.51 b	19.72 ± 3.16 a	11.72 ± 2.06 b	18.87 ± 5.98 a	14.43 ± 3.63 ab	0.0001
	2024	6.35 ± 1.17 a	13.35 ± 7.06 ab	10.35 ± 2.7 ab	18.58 ± 2.82 abc	11.02 ± 3.47 bc	16.45 ± 3.49 bc	16.93 ± 5.52c	0.0001

Note: The table presents tomato yield (t/ha) and mean ± standard error of nitrogen (N), organic carbon (OC), and phosphorus (P) concentrations (%) in stems and leaves under different fertilizer treatments (T1–T7) across two growing seasons. Superscript letters (a, b, c, etc.) denote statistically significant differences among treatments within the same year, based on post hoc comparison tests (Tukey HSD, $p < 0.05$). *** $p \leq 0.001$ (highly significant) ** $p \leq 0.01$ (very significant) * $p \leq 0.05$ (significant) ns: not significant ($p > 0.05$). The specific treatments are: Control (T1), 200 kg ha^{-1} of NPK (T2), 10 t ha^{-1} of ACARP compost (T3), 10 t ha^{-1} BSF frass compost (T4), 5 t ha^{-1} ACARP and 100 t ha^{-1} NPK combined (T5), 5 t ha^{-1} BSF frass compost with 100 kg ha^{-1} NPK (T6) and 5 t ha^{-1} ACARP with 5 t ha^{-1} BSF frass compost (T7). Nitrate (NO_3^-), Ammonium (NH_4^+), Nitrogen (N), Potassium (K+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Phosphorus (P), Organic Carbon (OC)

phosphorus availability addresses a critical nutrient constraint in Ghanaian soils (Bidzakin et al., 2023; Salomon et al., 2025). Our results mirror those of Menino et al. (2021), who noted that insect frass not only contributes phosphorus directly but also facilitates the solubilization of native phosphorus via organic acids. This biochemical mechanism is further supported by the presence of chitin and other organic compounds in frass, which stimulate soil microbial activity (Widyastuti et al., 2021). Microbes decompose these residues, producing organic acids and phosphatase enzymes that increase phosphorus solubilization and mobilization (Tan et al., 2021). Therefore, the evidence supports the conclusion that the most sustainable gains arise from combining BSF compost with mineral fertilizer rather than relying on either input alone.

The effect of BSF compost extended beyond macronutrients, as seen in the balanced increase in base cations (K^+, Ca^{2+}, Mg^{2+}) and the stability of soil pH. These findings are consistent with Zhu et al. (2023), who demonstrated that organic amendments provide a more sustained and even release of cations throughout the cropping season compared to mineral fertilizers. Furthermore, the unaltered pH observed aligns with

Table 5
Nutrient Use Efficiency following the application of different fertilizers, including NPK, traditional compost, and BSF frass to tomato crops.

Treatment	N input	Yield (t/ha)	ANUE (kg/kg)	APE (kg/kg)	NRE (ratio)	N Loss (%)
2023						
T2	200	16.05	33.71 ± 2.01 a	45.11 ± 3.70 a	0.45 ± 0.02 a	2.94 ± 0.12 a
T3	250	15.31	24.01 ± 1.28 b	85.70 ± 1.41 b	0.32 ± 0.01 b	54.12 ± 2.25 a
T4	360	14.89	15.51 ± 0.82c	51.89 ± 1.76c	0.28 ± 0.00c	57.70 ± 2.76 b
T5	225	13.28	17.68 ± 0.98c	37.15 ± 3.16 d	0.35 ± 0.01 d	32.57 ± 1.53c
T6	280	16.87	27.03 ± 0.64 d	39.46 ± 1.58 de	0.50 ± 0.01 d	15.56 ± 0.14 d
T7	305	15.73	21.07 ± 1.12 d	59.81 ± 0.90 e	0.40 ± 0.01 e	50.14 ± 4.14 e
			0.000***			
2024						
T2	200	12.51	34.68 ± 1.42 a	55.41 ± 4.60 a	0.48 ± 0.02 a	30.17 ± 1.54 a
T3	250	9.08	14.04 ± 0.68 a	137.00 ± 6.39 b	0.30 ± 0.02 a	83.96 ± 4.72 b
T4	360	15.24	26.86 ± 0.70 b	102.06 ± 3.20c	0.25 ± 0.02 b	69.66 ± 4.51 b
T5	225	10.14	20.30 ± 0.42c	72.61 ± 8.23c	0.33 ± 0.02c	65.60 ± 5.06 b
T6	280	16.24	38.11 ± 3.15 cd	74.17 ± 4.67 cd	0.52 ± 0.03c	43.44 ± 1.48c
T7	305	10.96	17.68 ± 0.49 d	66.51 ± 3.73 d	0.38 ± 0.01 d	68.66 ± 3.54 d
			0.000***			

Note: The table presents nitrogen input (kg ha^{-1}) and nitrogen use efficiency indicators under fertilizer treatments T2–T7 for two growing seasons. Values are presented as mean ± standard error, with superscript letters (a, b, c, etc.) indicating statistically significant differences among treatments within the same year ($p < 0.05$). The specific treatments are: Control (T1), 200 kg ha^{-1} of NPK (T2), 10 t ha^{-1} of ACARP compost (T3), 10 t ha^{-1} BSF frass compost (T4), 5 t ha^{-1} ACARP and 100 t ha^{-1} NPK combined (T5), 5 t ha^{-1} BSF frass compost with 100 kg ha^{-1} NPK (T6) and 5 t ha^{-1} ACARP with 5 t ha^{-1} BSF frass compost (T7). The parameters measured are: ANUE = Agronomic Nitrogen Use Efficiency (kg yield increase per kg N applied); APE = Apparent Nitrogen Recovery Efficiency (kg N uptake per kg N applied); NRE = Nitrogen Recovery Efficiency (unitless ratio); N Loss = Percentage of nitrogen lost from applied inputs (%). p-v values for significance are reported in the main text

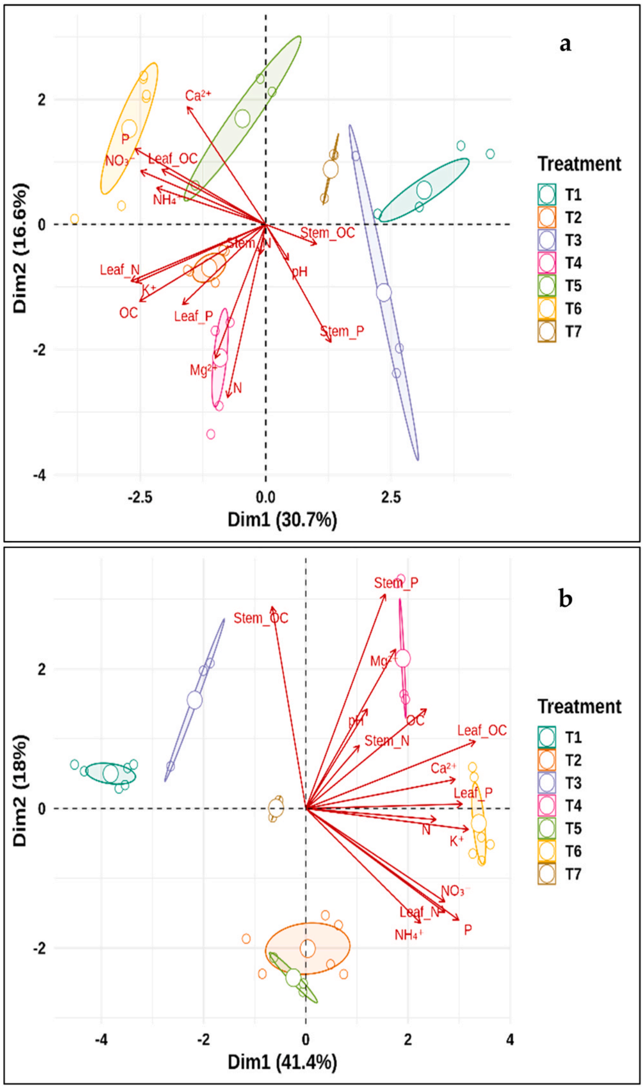

Fig. 3. Principal Component Analysis of Soil–Leaf–Stem Nutrient Interactions Under Integrated Fertilizer Treatments in Tomato Production in 2023 (a) and 2024 (b) growing seasons. Each point represents a composite plot-level observation, colour-coded by treatment. Arrows indicate the direction and strength (loading) of individual nutrient variables on the first two principal components (PC1 and PC2). Longer arrows denote stronger influence, and angles between arrows reflect correlations (smaller angles = positive correlation; opposing directions = negative correlation). The 95 % confidence ellipses around each treatment group visualize the consistency of nutrient profiles, tighter ellipses indicate lower variability and higher treatment stability. PC1 represents a soil fertility gradient dominated by cations (Ca^{2+}, Mg^{2+}, K^+) and NO_3^-, while PC2 captures the trade-off between soil pH/NH_4^+ and P allocation to plant tissues.

reports that frass applications do not significantly affect soil acidity (Antoniadis et al., 2023). This stability may be attributed to the buffering effect of organic matter in frass, which neutralizes acidity, enhances cation exchange capacity, and supports soil microbial communities. Such conditions create a biologically active rhizosphere, which further enhances nutrient cycling (Salomon et al., 2025). Nonetheless, it is important to acknowledge the potential drawbacks of BSF frass as high application rates may increase soil salinity, lead to ammonium accumulation, or induce phytotoxic effects, as noted in earlier studies (Watson et al., 2021). While these effects were not pronounced in our trial, they remain potential risks that should guide appropriate application rates and management strategies.

Improvements in soil fertility were directly linked to enhanced nutrient uptake in tomato plants, showcasing the biological relevance of the soil changes. The increase in nitrogen uptake under BSF compost treatments supports findings by Alromian (2020) and Qin et al. (2023), who demonstrated that slow-release of organic nitrogen better matches plant demand. Nevertheless, mineral fertilizer alone supplied readily available nitrogen that contributed to high agronomic efficiency but suffered from greater losses. The integrated BSF + NPK treatment combined these benefits, providing balanced nitrogen availability and reducing inefficiencies. Phosphorus uptake was especially pronounced and highly correlated with improved fertility scores. As highlighted by Srivastava et al. (2024), phosphorus plays a key role in flowering and fruit set, and organic sources provide more plant-available forms. Thus, BSF compost does not merely enrich the soil but effectively channels nutrients into plant tissues, with phosphorus uptake serving as a critical driver of productivity.

The uptake of potassium by tomato plants followed a similarly

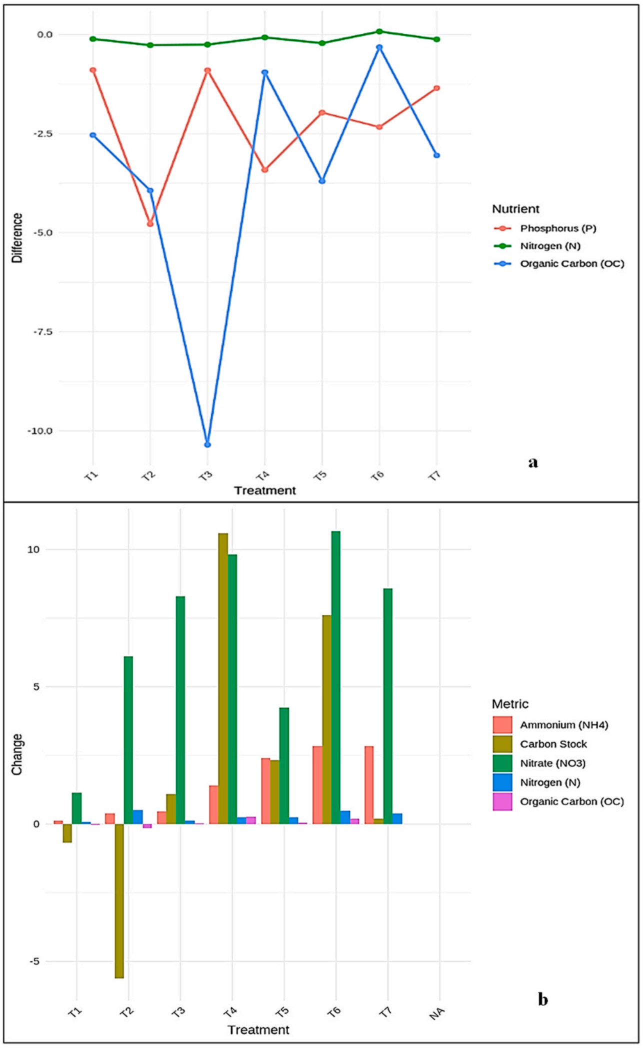

Fig. 4. **(a)** Nutrient-uptake distribution: stacked bars show the proportion of total plant uptake attributed to nitrogen (N), phosphorus (P) for each fertilizer treatment. Bars represent treatment means ± 1 SE (n = 3 field replicates). Letters above bars indicate significant differences in total uptake among treatments (one-way ANOVA followed by Tukey's HSD, $p < 0.05$). **(b)** Soil-carbon stock: bars give baseline-corrected changes in soil organic-carbon stock at 0–20 cm depth after two cropping cycles. Error bars are ±1 SE. Different letters denote significant treatment differences (ANOVA + Tukey, $p < 0.05$). Abbreviations: N = nitrogen; P = phosphorus; SE = standard error; SOC = soil organic carbon.

beneficial trend under BSF compost treatments, contributing to overall plant vigor and physiological resilience. Potassium is essential for several plant functions, including enzyme activation, stomatal regulation, and the movement of water and nutrients within the plant system. Our findings are in line with observations that organic amendments enhanced potassium uptake, leading to improved plant structure, stress tolerance, and nutrient transport (Ahmed et al., 2024). Although many studies focus on potassium's effect on fruit quality, our results emphasize its broader role in promoting robust vegetative growth and functional integrity in the whole tomato plant. Moreover, we observed higher nutrient concentrations at flowering than at harvest, aligning with studies that emphasized the importance of nutrient availability during reproductive development (Traoré et al., 2022). The gradual nutrient release and improved soil structure under BSF compost likely promoted better root proliferation and nutrient uptake efficiency, particularly during critical reproductive stages.

The most balanced nutrient uptake profile was consistently observed under the integrated BSF + NPK treatment, demonstrating the value of combining organic and inorganic inputs. This finding supports a growing body of literature that advocates for integrated soil fertility management (Schmitt and de Vries, 2020; Agustiyani et al., 2021; Anyega et al., 2021; Boudabbous et al., 2023; Gurung et al., 2024; Jasso et al., 2024). Long-term projections using ARIMA modeling showed that this combined strategy would maintain the highest fertility index through 2035. However, we acknowledge that such forecasts should be interpreted with caution, as ARIMA projections extend beyond the experimental timeframe and do not fully account for unpredictable biophysical or socioeconomic factors. This limitation underscores the need for continued long-term trials to validate projected outcomes.

The nitrogen use efficiency results highlight the superior performance of BSF compost combined with mineral fertilizer, which consistently achieved high yields, Agronomic Nitrogen Use Efficiency, and nitrogen recovery efficiency, while minimizing nitrogen losses across both seasons. This aligns with studies that emphasized the synergistic benefits of integrating organic and mineral sources to synchronize nutrient release with crop demand (Bidzakin et al., 2023; Salomon et al., 2025). In contrast, sole compost treatments showed high Agro-physiological Nitrogen Efficiency but poor Agronomic nitrogen use efficiency and substantial nitrogen losses, indicating delayed Nitrogen availability and inefficiencies typical of organic inputs with slower mineralization rates (Singh and Kumari, 2019; Salam et al., 2021). While mineral fertilizer alone performed well in Agronomic nitrogen use efficiency, its higher loss percentages suggest greater susceptibility to leaching or volatilization without organic matter to buffer nutrient release. These findings showed that the microbial activity and structural improvements driven by BSF compost create a buffering effect that enhances the efficiency of mineral nitrogen, making BSF + NPK the most effective treatment overall.

The highest yields recorded in the integrated BSF + NPK treatment across both seasons can be attributed to improved soil nutrient supply, enhanced microbial activity, and better soil structure that collectively support efficient nutrient uptake and translocation. Similar trends have been reported by Beesigamukama et al. (2021a) and Dzepe et al. (2022), who noted that integrating organic and inorganic sources enhances crop productivity through complementary nutrient release patterns. BSF compost provides a steady release of nutrients through microbial mineralization, while mineral fertilizers supply readily available forms during early growth stages. The presence of chitin and other organic compounds in the frass also stimulates beneficial soil microbes, improving enzymatic nutrient cycling and promoting root vigor (Quilliam et al., 2020). These mechanisms suggest that BSF compost, especially when combined with NPK, creates a balanced fertility environment that sustains higher tomato yields under semi-arid tropical conditions.

The PCA revealed a consistent and meaningful relationship between soil nutrient status and nutrient allocation in leaf and stem tissues across both seasons. Soils rich in exchangeable cations and nitrate, particularly under BSF + NPK and ACARP + NPK treatments, were associated with lower concentrations of organic carbon and phosphorus in vegetative tissues. This suggests a dilution effect, where luxury nutrient supply reduces the plant's need to accumulate carbon reserves and may also hinder phosphorus uptake, likely due to pH-induced fixation (Dzepe et al., 2022). Conversely, nutrient-poor plots, especially the control, showed higher tissue phosphorus relative to soil levels, indicating a stress-induced compensatory uptake mechanism (Dzepe et al., 2022). These patterns suggest that while compost-based treatments improve soil fertility, excessive alkalinity can reduce phosphorus (P) bioavailability in soil, even when total phosphorus levels are high (Beesigamukama et al., 2021a; Dzepe et al., 2022). The relatively higher tissue phosphorus observed under compost treatments may therefore be attributed not to alkalinity itself, but to organic matter–mediated mechanisms that enhance P solubilization and uptake. Therefore, integrating BSF compost with mineral fertilizers must be done with attention to phosphorus dynamics, either through targeted phosphorus application or pH buffering strategies to avoid hidden deficiencies. This nuanced soil–plant nutrient coupling highlights the importance of balanced fertility management for achieving both productivity and nutrient-use efficiency in circular farming systems.

These interactions were further evidenced through spatial analysis, which revealed patterns of nutrient uptake that mirrored the spatial clustering of soil fertility, particularly in BSF compost-treated plots. Moran's I statistics confirmed significant spatial autocorrelation, indicating that improvements in soil properties created localized "hotspots" of plant nutritional status. Organic amendments tend to generate persistent fertility zones due to microbial colonization and enhanced nutrient dynamics (Laribi et al., 2024). Moreover, the spillover effects observed beyond treated plots suggest lateral movement of soluble nutrients, a phenomenon also described by Antonangelo et al. (2021), who found such effects can extend up to two meters. This spatial diffusion of benefits implies that well-placed applications of BSF compost can positively influence broader farm areas, making it not only effective but also economically strategic.

Beyond agronomic improvements, the study highlights the ecosystem service potential of BSF compost through its contribution to long-term soil carbon sequestration. The increase in soil organic carbon and carbon stock under compost treatments indicates its role in stabilizing soil aggregates and increasing carbon residence time, critical components of climate-smart agriculture. These results align observed that the observed decomposition of frass-derived chitin and organic compounds improves soil organic matter content over time (Beesigamukama et al., 2020; Quilliam et al., 2020). Additionally, by converting organic waste into a valuable soil amendment, BSF systems close the nutrient loop, preventing methane and other greenhouse gas emissions from landfills (Ayilara et al., 2020). This positions BSF frass as more than a fertilizer; it is a dual-function input that enhances soil productivity and environmental resilience. Its role in promoting circular economy principles, by recycling waste, improving soil health, and sequestering carbon, underscores its value in sustainable agricultural development (Manan et al., 2024; Susilo et al., 2024).

This study is among the first field-based trials on BSF frass compost in West Africa and is novel in its integration of geospatial analysis in soil quality index and long-term forecasting of soil fertility effects. These elements provide unique insights into both agronomic performance and the sustainability implications of circular fertilizers. The findings have critical significance for sustainable agriculture in Ghana, where resource-limited farmers face declining soil fertility and limited access to mineral fertilizers. By demonstrating the effectiveness of BSF compost, especially when combined with NPK, this study identifies a circular pathway for improving productivity, soil health, and environmental sustainability in smallholder horticultural systems.

5. Conclusions

The present study demonstrated that the application of BSF compost, particularly when combined with mineral fertilizer, significantly enhanced soil fertility, tomato yield, and nitrogen recovery efficiency under the semi-arid conditions of Ghana. The BSF + NPK treatment consistently recorded the highest improvements in soil organic carbon, macronutrients and base cation availability, as well as the most balanced nutrient uptake across both seasons. These benefits translated into superior yields and higher nitrogen use efficiencies, confirming the added value of integrating BSF compost with mineral fertilizers compared to sole applications of either input. Sole BSF compost also improved soil organic matter, phosphorus availability, and nutrient uptake, contributing positively to soil fertility and crop performance. However, its slower nutrient release limited agronomic nitrogen use efficiency relative to mineral fertilizer, underscoring the importance of integrated nutrient management strategies. In conclusion, BSF compost shows strong potential as a circular organic fertilizer, especially when integrated with mineral fertilizers. This combined approach not only maximizes tomato productivity and nitrogen recovery efficiency but also enhances soil health, contributing to circular and climate-resilient agriculture in West Africa. Future studies should investigate its long-term impacts across diverse soil types and cropping systems, including measurements of soil microbial activities and greenhouse gas emissions, to fully understand its impacts on soil health and climate.

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CRediT authorship contribution statement

Malick Niango Ba: Writing – review & editing, Validation, Resources. **Ramasamy Srinivasan:** Writing – review & editing, Validation. **Lukas Pawera:** Writing – review & editing, Methodology. **Plange Ato Bart:** Writing – review & editing. **Baffour Nicholas Kyei:** Writing – review & editing. **William Amponsah:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Paul Alhassan Zaato:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors 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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Data availability

Data will be made available on request.

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