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Do rates matter? Validation of insect frass fertilizer rates in a vegetable intensified push-pull technology for optimal sustainable production

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Push-pull system intensification with vegetables (VIPPT) has contributed significantly in maintaining good control of lepidopteran pests and parasitic weeds with additional food and nutritional security benefits. However, the impact of integration of different rates of black soldier fly frass fertilizer (BSFFF) in the VIPPT to enhance productivity, has not been explored. This study investigated the effects of different BSFFF application rates on growth performance, pest infestation severity, diversity of natural enemies and yield of kale (*Brassica oleracea* L. var. *acephala*) grown under VIPPT in two agroecological zones. Plants were grown in soils amended with five different levels of BSFFF (0, 50, 100, 150 and 200) kg N ha⁻¹, blends with inorganic fertilizers, (Di-ammonium phosphate (DAP) and Nitrogen, Phosphorous and Potassium (NPK)), and unfertilized soil (control). Across the two sites, plants treated with 200 BSFFF exhibited faster growth and higher yield (by 7% and 82%) compared to 150BSFFF and 0BSFFF, respectively. Similarly, aphid infestation was lower in the 200BSFFF treatment (by 64% and 1%) compared to inorganic fertilizer and 0BSFFF. Additionally, natural enemies such as Coleoptera (35% and 97%), Hemiptera (17% and 97%) and Diptera (100% and 44%) were more abundant in 200BSFFF than 0BSFFF and inorganic fertilizer treatments, respectively. Our findings demonstrate that integration of VIPPT and BSFFF at an application rate of 200 Kg N ha⁻¹ BSFFF significantly improves growth and yield of kales while reducing the severity of pest infestation and conserves natural enemies of key cruciferous pests. The synergistic effects of these technologies hold great promise towards sustainable vegetable production, environmental and biodiversity conservation.

KEYWORDS

agrobiodiversity, *Hermetia illucens*, kale, pest management, regenerative agriculture

1 Introduction

Kale (*Brassica oleracea* L. var. *acephala*) is a leafy vegetable with direct contribution to food security, nutrition, health, and income generation particularly in the tropical and subtropical regions (Šamec et al., 2019; Peris and Kiptoo, 2017; Mutiga et al., 2010). With over 17 vital nutrients, it is ranked 15th out of 47 powerhouse vegetables (CDC, 2014). It is popularly grown and consumed in Kenya due to its rich supply of vitamins, minerals, amino acids, cholesterol-free properties, low fat and calories. It also contains phytochemicals that have been linked to reduced risk of cancer and other chronic diseases, due to antioxidant properties and high dietary fiber content (Šamec et al., 2019; Nedi, 2021). Kale is one of the easiest crops to grow since it requires little labor and minimal inputs (Lans et al., 2012; Canwat et al., 2021). Its economical production processes and market prices, makes it affordable for consumers hence it is widely sold in cities and consumed in almost all households providing income and employment especially for youth and women (Ngolo et al., 2019; Canwat et al., 2021). Kale is also resilient to adverse weather conditions, hence it is grown in nearly all regions of Kenya, particularly in Kiambu (Lagerkvist et al., 2012; HCD, 2019; Mutua et al., 2024).

The productivity of kale in Kenya and most of other Sub-Saharan African (SSA) countries is constrained by a number of challenges including poor soil fertility, pests and diseases which are being exacerbated by the changing climatic conditions (Mutiga et al., 2010; Wortmann et al., 2019). To curb these challenges, farmers rely on inorganic fertilizers and pesticides which are costly, inaccessible and require a lot of energy to produce (Fairhurst, 2012; Machekano et al., 2019). In addition, the continuous use of these pesticides and inorganic fertilizers has adverse effects to the environment and human health (Mutuma et al., 2014; Sairam et al., 2023). Thus agroecology as an integrated strategy to rethinking agri-food systems for social, environmental, economic, and governance sustainability, is being promoted as a regenerative strategy for agri-food system transformation and sustainability (Struik et al., 2014; Struik and Kuyper, 2017). One such agroecological approaches is push-pull technology (PPT), cropping system which employs a stimulo-deterrent behavioral manipulation of insect pests and their natural enemies to protect the main crop. In this system, insect pests are deterred from the main crops through the production of volatile organic compounds (VOCs) by the desmodium (*Desmodium intortum*) intercrop (push component). On the other hand, the diverted pests are lured towards surrounding trap crops for oviposition, usually Brachiaria grass (*Brachiaria brizantha*) or Napier grass (*Pennisetum purpureum*) where their larval development is halted (Pickett et al., 2014). Agroecological intensification using push-pull technology helps reduce production risks by controlling lepidopteran pests such as fall armyworm (*Spodoptera frugiperda*) and stemborers, minimizing crop losses (Chepchirchir et al., 2018; Kassie et al., 2018; Martin-Guay et al., 2018). Belowground, desmodium provides nitrogen to the main crop through biological nitrogen fixation, prevents soil degradation by providing soil cover and suppress parasitic striga weed (*Striga*

hermonthica) by inducing suicidal germination eventually depleting the striga seed bank in the soil (Khan et al., 2016; Mutyambai et al., 2019). To further enhance nutritional diversity and farm productivity, high value vegetables have been incorporated into PPT to form the Vegetable Integrated Push-Pull Technology (VIPPT) (Chidawanyika et al., 2023). VIPPT meets farmers' needs while promoting nutrition, sustainability, and environmental protection. It also helps reduce pests like diamondback moth (*Plutella xylostella*) and cabbage aphids (*Brevicoryne brassicae*) in vegetables like kale and tomatoes (*Solanum lycopersicum*) (Chidawanyika et al., 2025).

To address soil fertility, insect-based recycling of bio-waste into nutrient-rich organic fertilizer has been poised as an effective alternative in closing nutrient loops (Beesigamukama et al., 2023; Salomon et al., 2025). These insects include black soldier fly (BSF) *Hermetia illucens* which is widely distributed across the tropics with high ability to convert waste efficiently to organic frass fertilizer and high-quality livestock feed (Dobermann et al., 2017). According to European Union Commission Regulation (EU) 2021 frass is defined as a mixture of excrements derived from farmed insects, the feeding substrate, parts of insects, dead eggs and with a content of dead insects of not more than 5% in volume and not more than 3% in weight (Elissen et al., 2023). Like other organic fertilizers, BSFFF increases the organic matter, improves soil fertility, structure, aeration, water holding capacity, nutrient availability, releases nutrients at a slow, consistent rate and protects soil against agents of erosion such as wind and water (Han et al., 2016).

Due to its higher nutrient value, BSFFF has been reported to improve growth and production of various crops, contributing to higher economic returns, poverty alleviation, nutritional and food security among smallholder farmers (Anyega et al., 2021; Tanga et al., 2021; Beesigamukama et al., 2022). Frass fertilizer boosts nutrient levels in the soil that contributes to soil health through organic matter content and nutrient sequestration leading to increased carbon, enzyme and microbial activities (Klammsteiner et al., 2020). It also contains plant-beneficial bacteria that directly promote plant growth by decomposing organic matter, fixing nitrogen, and producing plant hormones (Yang et al., 2024; Jiang et al., 2025). Due to these properties, it enhances plant growth translating to higher yield (Chepkorir et al., 2024; Ashworth et al., 2025; Chia et al., 2025; Kagehi et al., 2025).

Insect frass also contains significant amounts of other components such as chitin from the insects' skin that protects plants against diseases, pathogens and physiological disorders (Quilliam et al., 2020). It also contains biomolecules and microorganisms that accelerate plant resistance to biotic stress (Poveda, 2021). It upregulates defense genes in crops, positively impacting direct plant defense traits (Mutyambai et al., 2025). It further acts as phytofortifier enhancing systemic- and chitin induced defense through hormones such as salicylic acid and ethylene that enhance plants resistance to diseases and insect pest (Poveda et al., 2019; Blakstad et al., 2023). Its application to the soil therefore translates to activation of systemic defense genes that acts as immune stimulants in plants (Blakstad et al., 2023). Insect frass also contain volatile compounds that attract natural enemies of

insect pests such as parasitoids and predators hence reduction in pest populations (Zunzunegui et al., 2025). Frass contains nematicidal compounds that have been reported to suppress nematode infestation and population in crops as potatoes and spinach (Anedo et al., 2024; Anedo et al., 2025; Kisaakye et al., 2024). BSFFF has been applied on different crops with varying rates recommended for use, either alone or in combination with other fertilizers (Dzepe et al., 2022; Anyega et al., 2021).

A recent study by Omuse et al. (2025) showed that integration of VIPPT and BSFFF boosts the diversity of beneficial soil-dwelling arthropods such as microbivores, predators and detritivores, key players in maintaining soil health. However, the potential synergistic effects of integrating different rates of BSFFF with VIPPT to optimize crop performance and pest suppression remains unexplored. This study, therefore, investigated the combined effects of different application rates of BSFFF and VIPPT on kale growth performance, pest suppression, biodiversity of pests' natural enemies and overall kale yield, to inform integrated nutrient and pest management strategies for sustainable vegetable production.

2 Materials and methods

2.1 Experimental sites

Field experiments were carried out in two sites at Kenya Agricultural and Livestock Research Organization (KALRO), Embu County and Murang'a University, Mariira campus in Muranga county both in Central Kenya. The experiments were carried out for two cropping seasons, March-May 2024 for the first season and October-December 2024 for the second season. Embu county lies under agroclimatic zone IV within coordinates latitude:

S 00° 30.276' longitude: E 037° 27.377'. It receives an average rainfall of 1250mm annually. Temperature ranges between 12-30°C with a mean of 21°C annually with an elevation of 1510m above sea level. The soils are well drained, very deep, and well-structured red volcanic soils (Kisaka et al., 2015). Murang'a County lies in agroclimatic zone III within coordinates latitude: S 00° 48.362' longitude: E 036° 56.168' with an elevation of 1980 m above sea level. Annual rainfall ranges between 750-1700mm while annual temperature ranges between 10-25 °C (Bitok et al., 2023). The Data Access Viewer interface (<https://power.larc.nasa.gov/data-access-viewer/>), the NASA POWER (Prediction of Worldwide Energy Resources) Meteorological database was accessed online and used to acquire the current daily weather data for the two consecutive cropping seasons. Daily mean air temperature (°C) and total daily rainfall (mm/day) were the weather variables that were included. These meteorological factors were chosen because they have been shown to have an impact on various aspects under study (Zhang and Zhang, 2012; Forchibe et al., 2023) (Figure 1).

2.2 Experimental materials and land

Companion crops for the vegetable integrated push-pull technology: green leaf desmodium and brachiaria grass were established before the main crop during the short rains season (October to December 2023). Desmodium was planted using both seeds and cuttings. Cuttings were obtained from KALRO Embu while seeds were obtained from Simlaw Seed Company. Brachiaria was established using cuttings that were also obtained from KALRO, Embu. The main crops planted were maize (*Zea mays*) as cereal and kale as vegetable. Kale seeds (simlaw select- a fast growing and high yielding hybrid variety) were obtained from Simlaw Seed Company,

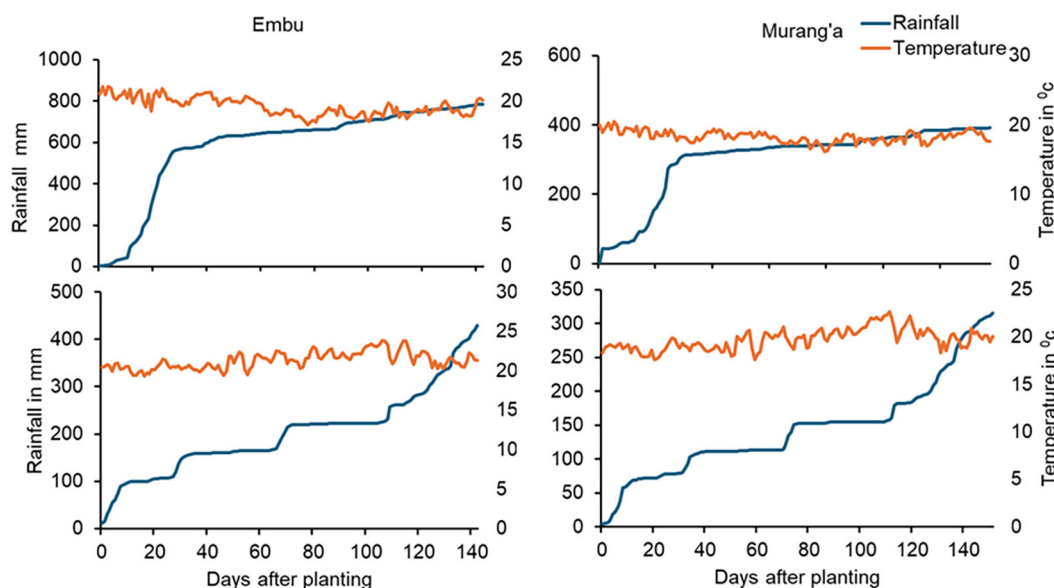


FIGURE 1

Weather data for the two study sites during the two planting seasons: (A) and (B) during long rains (April – August 2024) and (C) and (D) during short rains (November 2024–April 2025).

while maize seeds (SC Duma 43) were also sourced from the same company. The kale seeds were planted in a nursery for four weeks before being transplanted to the respective experimental sites. The experiment involved two types of fertilizers: organic fertilizer (black soldier fly frass fertilizer) and inorganic fertilizer (Diammonium phosphate (DAP) and Nitrogen, Phosphorous and Potassium (NPK) 17:17:17). BSFFF was obtained from Regen organics while the inorganic fertilizers were sourced from the Kenya Farmers Association Limited. The nitrogen content of the BSFFF was determined using the Kjeldahl method, which was then used to calculate the appropriate application rate (Sáez-Plaza et al., 2013). Before the experiments were established, soil sampling was carried out. The field was divided into three subsections and four samples were collected from each subsection using the zigzag method. These samples were thoroughly mixed to obtain a single representative composite sample, which was placed in khaki bags and sent to Société Générale de Surveillance (SGS) Kenya Limited Laboratory Services for analysis of physical and chemical properties. Results showed that soils from the Embu site contained higher nitrogen, organic carbon, phosphorus, potassium, magnesium and electrical conductivity compared to the soil from Murang'a site (Table 1).

2.3 Experimental setup

Experimental trials were established with seven treatments: five different levels of BSFFF applied in the VIPPT (0, 50, 100, 150 and 200BSFFF kg N ha⁻¹) an equivalent of 0, 2000, 4000, 6000 and 8000 BSFFF kg ha⁻¹; intercrop of kale and maize fertilized with inorganic fertilizer (DAP and NPK) applied at conventional rates of 125 and 150 kg ha⁻¹ respectively and unfertilized soil (control). The BSFFF application rates were denoted as 0BSFFF, 50BSFFF 100BSFFF,

150BSFFF and 200BSFFF corresponding to the respective nitrogen levels. The experiment was laid out in a randomized complete block design (RCBD). Each treatment was replicated four times in Embu and three times in Murang'a depending on available land. Experimental blocks were separated by 2 m boundaries, with individual plots measuring 5.5m by 5.5m and a boundary of 1.5m between the plots. Bracharia (pull crop) was planted along plot boundaries, for plots with the push-pull treatments. Within plots, green leaf desmodium (push crop) was planted at 75 cm spacing during the short rains of October-December 2023. After establishment of the companion crops, maize and kale were planted between desmodium rows. Kale seedlings were planted at 50 x 75 cm spacing (one seedling per hole), while maize was planted at 30 x 75cm spacing (one seed per hole). During planting, the amount of fertilizer to be applied for each particular treatment was calculated based on the available nitrogen in the BSFFF that was determined using in the laboratory using Kjeldalhs method (Kjeldahl, 2013.) BSFFF was applied in the furrows and mixed thoroughly with soil in the relevant treatments. DAP was also applied at planting and mixed with soil in plots under inorganic fertilization, followed by NPK topdressing two weeks later. Gapping was done seven days after planting to achieve maximum plant population. The crops were primarily rainfed, with supplemental irrigation once per week during dry spells to reduce water stress and support growth.

2.4 Data collection

2.4.1 Kale growth and yield

Kale growth was monitored by measuring plant height, leaf area, chlorophyll content, stem diameter and counting the number of leaves. Nine plants per plot were randomly selected and tagged for repeated measurements. Plant height was measured using tape measure from the soil surface to the apex of the plant. The number of leaves were determined by counting the photosynthetically active leaves while stem diameter was measured using Vanier calipers placed on the plant stem, 5cm from the soil surface. Leaf chlorophyll content was estimated with a SPAD chlorophyll meter (Konica Minota 502, Chiyoda, Japan) on the three topmost leaves that were fully opened, and the average score was obtained. Leaf length and width were determined by measuring the three topmost leaves that were fully opened by placing the tape measure at the broadest part of the leaf for leaf width, and from the petiole base to the apex for leaf length. The leaf area was then determined by multiplying the leaf width and length. Data collection was done fortnightly from the fourth to the twelfth week after transplanting. Kale yield was determined by counting the number of marketable leaves harvested per plot and recording their fresh weight. To determine the dry weight per plot, leaf samples were collected from each plot weighed and stored in khaki bags. Samples were pre-dried in greenhouse and then oven-dried at 60°C for 48 hours after which dry weight was recorded. The dry sample weight was used to calculate the total dry weight per plot. In addition, unmarketable leaves were counted and weighed separately to account for losses.

TABLE 1 Selected physiochemical properties of soil from the two sites and the black soldier fly frass fertilizer used during the experiment.

Parameters	Test soil Embu	Test soil Murang'a	BSFFF test sample
PH	4.95	4.56	7.64
EC (mmhos/cm)	0.14	0.12	11.02
Total nitrogen (%)	0.46	0.2	3.41
Total organic carbon (%)	4.59	2.21	33.48
Phosphorus(mg/kg)	15.01	3.01	8400
Potassium (mg/kg)	327.44	124.60	15500
Magnesium (mg/kg)	126.27	60.89	2521.10
Calcium (mg/kg)	588.04	239.34	10926.54
%clay	53.05	37.49	–
%silt	19.97	24.99	–
%sand	26.98	37.52	–
Textural class	Clay	Clay loam	–

EC, Electrical conductivity, TOC, total organic carbon.

Harvested leaves were sorted into two different batches: (i) marketable leaves, consisting of healthy leaves and those with low to moderate damage, (ii) non-marketable (rejected) leaves, consisting of severely damaged or diseased leaves, which were classified as non-marketable (rejected). For quality assessment, three independent individuals categorized the leaves after each harvest based on physical judgement (Chidawanyika et al., 2025). Total yield per season was determined as the sum of all the harvests.

2.4.2 Pest infestation, damage severity and abundance of natural enemies

Pest infestation was assessed by scouting two key pests of kale, cabbage aphid (*B. brassicae*) and diamondback moth (*Plutella xylostella*). Pest abundance was determined by counting the number of pests and colonies in the nine tagged plants per plot. Severity of pest damage was assessed using standardized damage score scales: aphid damage was scored on a 1–4 scale following Nagrare et al. (2011) while diamondback moth damage was scored on a 1–5 scale following Eddie and Olubayo (2010). Natural enemies were assessed by scouting both inside the plots and in the companion crops. Their abundance was estimated by direct counts and sweep net collections. Specimen were preserved in 95% ethanol in Falcon tubes and taken to the laboratory for identification using morphological keys (Hullé et al., 2020). Abundance was expressed as the average number of individuals per plot.

2.5 Data analysis

Before analysis, all the data was subjected to normality test using Shapiro-Wilk test. After normality test, data on kale growth (number of leaves, leaf area, plant height, stem diameter), chlorophyll concentration, yield; infestation severity and abundance of pests and their natural enemies were analyzed using linear mixed-effect model from the package *lme4*. Mean separation was done using Tukey's HSD test using "cld" function from the "multicompView" package. In the model, sampling time and fertilizer treatments were considered fixed effects, while replication was a random effect. All statistical analysis was conducted using R software version R.4.5.0 (R Core Team, 2022).

3 Results

3.1 Influence of different rates of black soldier fly frass fertilizer on growth of kale

3.1.1 Number of leaves

The number of kale leaves varied significantly across growth stages and fertilizer treatments at both sites. At Embu, leaf number differed significantly with fertilizer application during both seasons (long rains $\chi^2=60.448$, $df=24$, $P<0.001$, short rains $\chi^2=2825.32$, $df=24$, $P<0.001$). A similar trend was observed at Murang'a (long rains $\chi^2=155.84$, $df=24$, $P<0.001$, short rains $\chi^2=916.64$, $df=24$,

$P<0.001$). Leaf number also varied significantly across growth stages (Embu: long rain $\chi^2=16671.33$, $df=4$, $P<0.001$, short rain $\chi^2=65937.8$, $df=4$, $P<0.001$; Murang'a: long rain $\chi^2=2550.90$, $df=4$, $P<0.001$, short rain $\chi^2=7344.46$, $df=4$, $P<0.001$) (Table 2). Moreover, the interaction between treatments and the number of kale leaves was significant at both sites (Embu: long rain: $\chi^2=236.71$, $df=6$, $P<0.001$, short rain $\chi^2=7289.4$, $df=6$, $P<0.001$; Murang'a: long rain $\chi^2=429.29$, $df=6$, $P<0.001$, short rain $\chi^2=2005.88$, $df=6$, $P<0.001$). Leaf number increased cumulatively with crop age, reaching maxima of 23–29 leaves (long rains) and 24–38 leaves (short rains) in Embu and 11–18 leaves (long rains) and 9–22 leaves (short rains) in Murang'a at twelve weeks after transplanting. Kales grown with inorganic fertilizer (DAP + NPK) consistently produced the highest leaf numbers across both seasons and sites (Table 2). Among organic treatments, higher BSFFF application rates (150 and 200 Kg N ha⁻¹) resulted in significantly more leaves compared to lower rates (50 and 100 Kg N ha⁻¹). The 200 Kg N ha⁻¹ BSFFF treatment produced the highest number of leaves in both Murang'a and Embu during season one (Table 2).

3.1.2 Plant height

Kale plant height was significantly influenced by fertilizer treatments across sites and seasons. In Embu, significant differences were observed during both the long rains ($\chi^2=1543.65$, $df=6$, $P<0.001$) and short rains ($\chi^2=1514.80$, $df=6$, $P<0.001$). Similar effects were recorded in Murang'a (long rains: $\chi^2=14822.7$, $df=6$, $P<0.001$; short rains: $\chi^2=7966.6$, $df=6$, $P<0.001$). Plant height also varied significantly due to the interaction between treatments and growth stages (Embu: long rain $\chi^2=4831.14$, $df=4$, $P<0.001$; short rains $\chi^2=8031.04$, $df=4$, $P<0.001$; Murang'a: long rains $\chi^2=8488.2$, $df=4$, $P<0.001$; short rains $\chi^2=11040.0$, $df=4$, $P<0.001$). Additionally, fertilizer treatments had a significant effect on plant height across growth stages (Embu: long rains $\chi^2=631.23$, $df=24$, $P<0.001$; short rains $\chi^2=742.58$, $df=24$, $P<0.001$; Murang'a: long rains $\chi^2=1310.8$, $df=24$, $P<0.001$; short rains $\chi^2=2011.6$, $df=24$, $P<0.001$). Plots treated with inorganic fertilizers produced the tallest plants in both seasons at Embu. In Murang'a, however, the tallest plants were recorded in plots amended with 150Kg N ha⁻¹ BSFFF during season one (Table 3). Among BSFFF treatments, 200 Kg N ha⁻¹ produced the tallest plants in season one in Embu, while 150 Kg N ha⁻¹ BSFFF consistently produced the tallest plants across both seasons in Murang'a. In Embu during season two, 200 Kg N ha⁻¹ BSFFF also supported the tallest plants at weeks 10 and 12 (Table 3).

3.1.3 Leaf area

Kale leaf area varied significantly with fertilizer treatments across both sites and seasons. In Embu, significant differences were observed during the long rains ($\chi^2=1613.53$, $df=6$, $P<0.001$) and short rains ($\chi^2=13454$, $df=6$, $P<0.001$). At Murang'a, similar effects were recorded (long rains: $\chi^2=5604.82$, $df=6$, $P<0.001$; short rains: $\chi^2=7860.1$, $df=6$, $P<0.001$). The interaction between fertilizer treatments and growth stages was also significant at both sites (Embu: long rains: $\chi^2=706.92$, $df=24$, $P<0.001$; short rains: $\chi^2=3216$, $df=24$, $P<0.001$; Murang'a: long rains: $\chi^2=235.11$, $df=24$, $P<0.001$;

TABLE 2 Number of kale leaves influenced by different fertilizer treatments in vegetable intensified push-pull technology in different agroecological zones in Kenya.

Season	Treatment	Embu					Murang'a				
		Weeks after planting					Weeks after planting				
		4	6	8	10	12	4	6	8	10	12
Long rains (April – August 2024)	0BSFFF+ VIPPT	5.5±0.29a	6±0.41a	15±0.41a	23.25±0.48a	29.75±0.25a	3±0a	3±0a	5.33±0.33ab	8.67±0.33a	12±0.58a
	50BSFFF+ VIPPT	5.25±0.25a	7±0.41a	17.5±0.65bc	25.75±0.75ab	32.75±1.11ab	4.33±0.33abc	4.33±0.33ab	5.67±0.88ab	10±0.58ab	13±0.58a
	100BSFFF+VIPPT	6.25±0.48a	8±0.41ab	16.25±0.48ab	25.25±0.85ab	34±0.71bc	4.67±0.33abc	5.33±0.33bc	6.67±0.33abc	11.67±0.67abc	17±0.58b
	150BSFFF+VIPPT	5.5±0.65a	6.25±0.25a	16±0.41ab	24.5±0.65ab	32±0.91ab	6±0bc	6.33±0.33cd	7.33±0.67bc	12±0.58bc	18±0.58b
	200BSFFF+VIPPT	6.25±0.63a	7.25±0.25ab	16.5±0.5ab	24.25±0.85ab	32.5±1.26ab	5.33±0.33bc	5.67±0.33bc	8.67±0.67c	13.33±0.88c	21.67±1.2c
	Control	6.5±0.5ab	7.25±0.75ab	17.75±0.63bc	27.27±0.48bc	33.5±0.65abc	4±0.58ab	4.33±0.33ab	4.33±0.33a	8.67±0.67a	11.33±0.33a
	Synthetic	9±0.91b	9.25±0.48b	19±0.41c	29±0.71c	37.25±0.48c	6.33±0.88c	7.33±0.3d	8±0.58bc	12.33±0.88bc	18.67±0.bc
	DF	6	6	6	6	6	6	6	6	6	6
	F value	29.95	5.91	6.83	7.89	7.48	6.62	21.72	7.19	7.44	31.84
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.001	=0.01	<0.001	<0.001
Short rains (November 2024- April 2025)	0BSFFF+ VIPPT	5±0a	9.5±0.29ab	18±0d	24±0c	29.75±0.25b	4.33±0.33a	5±0b	4±0a	7±0a	11.67±0.33b
	50BSFFF+ VIPPT	6±0b	10±0ab	16.25±0.25ab	26.25±0.25d	32±0c	4.33±0.33a	5.33±0.33b	6.67±0.33b	10.67±0.33b	14.67±0.33c
	100BSFFF+VIPPT	6.25±0.25b	9.25±0.25a	16.5±0.29ab	22.25±0.25b	30.5±0.29b	6±0bc	7±0cd	8±0bc	11.67±0.33bc	16.67±0.33d
	150BSFFF+VIPPT	8±0c	12.75±0.25c	20±0d	26.75±0.25d	35.75±0.25d	6±0bc	7.33±0.33d	9.3±0.33c	12±0cd	16.67±0.33d
	200BSFFF+VIPPT	7.75±0.25c	10.5±0.29b	17±0b	23.25±0.25bc	30.5±0.29b	6.33±0.33c	7.33±0.33d	8.67±0.33c	13±0d	18±0d
	Control	5.5±0.29ab	9.25±0.25a	15.75±0.25a	20.25±0.25a	24±0a	4.33±0.33a	3.33±0.33a	4.67±0.33a	6.33±0.33a	9.33±0.33a
	Synthetic	7.5±0.29c	15±0d	27.75±0.25e	37.25±0.25e	38.75±0.25e	4.67±0.33ab	6±0bc	8.67±0.33c	15.67±0.33e	22.33±0.33e
	DF	6	6	6	6	6	6	6	6	6	6
	F value	200.14	565.41	2752.60	3459	2611.10	64	34.25	332.80	170.80	137.30
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic=inorganic fertilizer; Control=unfertilized plot. Per column, mean (± standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

TABLE 3 Kale plant height (cm) as influenced by different fertilizer treatment in vegetable intensified push-pull technology (VIPPT) in different agroecological zones in Kenya.

Seasons	Treatment	Embu					Murang'a				
		Weeks after planting					Weeks after planting				
Long rains(April-August 2024)		4	6	8	10	12	4	6	8	10	12
	0BSFFF+ VIPPT	10.93±0.41b	12.62±0.41a	13.59±0.56a	19.53±0.44ab	20.11±0.75a	5.79±0.1a	6.1±0.04a	9.69±0.09a	11.5±0.17b	12.49±0.1b
	50BSFFF+VIPPT	13.61±0.54c	16.74±0.2cd	16.93±0.51b	18.67±0.3ab	21.88±0.25ab	6.63±0.31a	7.63±0.31b	11.58±0.15b	17.66±0.12c	15.31±0.26c
	100BSFFF+VIPPT	10.91±0.51b	13.14±0.27ab	21.52±0.79cd	20.97±0.76bc	25.43±0.67c	11.77±0.12b	12.28±0.25c	15.4±0.2c	15.53±0.03d	18.41±0.29d
	150BSFFF+VIPPT	13±0.47bc	14.77±0.62bc	19.53±0.37c	22.23±0.5c	23.58±0.54bc	14.56±0.23d	15.56±0.23e	17.26±0.12e	20.68±0.16f	22.52±0.17f
	200BSFFF+VIPPT	17.1±0.68d	18.81±0.72e	23.14±0.68d	28.14±0.42d	28.33±0.4d	12.69±0.08bc	13.55±0.21d	15.46±0.09c	17.66±0.16e	20.54±0.17e
	Control	8.12±0.56a	11.48±0.39a	15.64±0.29ab	18.3±0.49a	20.37±0.6a	6.52±0.22a	8.52±0.22b	9.14±0.05a	12.72±0.11a	10.33±0.16a
	Synthetic	12.81±0.63bc	16.98±0.27de	26.59±0.51e	30.3±0.86d	32.83±0.58e	13.43±0.23c	14.27±0.06d	16.43±0.23d	17.65±0.08e	25.65±0.15g
	DF	6	6	6	6	6	6	6	6	6	6
	F value	25.81	35.91	67.37	417.15	67.73	2085.6	1827.70	3159.80	948	772.60
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Short rains (November 2024-April 2025	0BSFFF+ VIPPT	14.61±0.07b	19.62±0.08c	21.53±0.12b	24.88±0.14ab	29.64±0.12b	9.64±0.25bc	10.49±0.2ab	10.79±0.12a	11.66±0.09a	12.61±0.18a
	50BSFFF+ VIPPT	15.38±0.07c	17.62±0.14b	22.71±0.1c	26.64±0.11b	33.55±0.03d	8.66±0.04ab	13.46±0.28c	17.43±0.04d	18.38±0.16d	19.44±0.1c
	100BSFFF+VIPPT	15.56±0.18c	17.64±0.12b	22.69±0.1c	28.6±0.14bc	32.55±0.15c	9.22±0.53abc	17.6±0.2d	18.64±0.05e	19.64±0.13e	21.09±0.16d
	150BSFFF+VIPPT	15.42±0.19c	23.33±0.04c	26.61±0.19d	28.56±0.14bc	32.78±0.07cd	11.67±0.2d	17.36±0.24d	20.61±0.16f	21.31±0.08f	23.89±0.05f
	200BSFFF+VIPPT	14.28±0.18b	19.5±0.12d	26.44±0.1d	31.41±2.56c	35.19±0.12e	10.18±0.06c	18.92±0.1e	19.49±0.19e	20.77±0.31f	22.48±0.04e
	Control	12.28±0.11a	13.16±0.16a	19.02±0.05a	22.01±0.02a	28.71±0.1a	8.69±0.2ab	10.0±50.05a	11.73±0.39b	14.14±0.06b	14.62±0.24b
	Synthetic	12.49±0.07a	23.11±0.09d	29.95±0.07e	37.38±0.14d	43.45±0.18f	8.4±0.12a	11.24±0.08b	15.62±0.1b	16.78±0.08c	20.74±0.23d
	DF	6	6	6	6	6	6	6	6	6	6
	F value	625.20	5661.10	5812.20	154.18	9733.30	125.27	2519.60	2484	3277.80	4087.30
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic =inorganic fertilizer; Control=unfertilized plot. Per column, mean (± standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

short rains: $\chi^2=1363.0$, $df=24$, $P<0.001$). Additionally, growth stages alone significantly influenced leaf area during both seasons (Embu: long rains $\chi^2=10084.90$, $df=4$, $P<0.001$; short rains $\chi^2=2530.6$, $df=4$, $P<0.001$; Murang'a: long rains $\chi^2=1635.13$, $df=4$, $P<0.001$; short rains $\chi^2=5385.0$, $df=4$, $P<0.001$). Plots amended with inorganic fertilizer produced the largest leaf area at both sites in both seasons (Table 4). Among BSFFF treatments, 200 Kg N ha⁻¹ BSFFF resulted in the largest leaf area during season one at all sites. In season two, plants in plots amended with 150 Kg N ha⁻¹ BSFFF had the largest leaf area in both sites, although in Murang'a this did not differ significantly from the 200 Kg N ha⁻¹ BSFFF treatment. At twelve weeks after planting, 200 Kg N ha⁻¹ BSFFF produced the largest leaf area in Embu (season one) and in Murang'a (season two), whereas 150 Kg N ha⁻¹ BSFFF resulted in the largest leaf area in Murang'a (season one) and in Embu (season two) although this did not differ significantly with 200 kg N ha⁻¹ in Murang'a (Table 4).

3.1.4 Stem diameter

Stem diameter of kale varied significantly across both seasons and sites in response to fertilizer treatments. In Embu, significant differences were observed during the long rains ($\chi^2=1481.15$, $df=6$, $P<0.001$) and short rains ($\chi^2=1589.78$, $df=6$, $P<0.001$). In Murang'a, similar significant effects were recorded (long rains: $\chi^2=2965.30$, $df=6$, $P<0.001$; short rains $\chi^2=2126.56$, $df=6$, $P<0.001$). Stem diameter also varied significantly with growth stages (Embu: long rains $\chi^2=6865.69$, $df=4$, $P<0.001$; short rains $\chi^2=17151.65$, $df=4$, $P<0.001$; Murang'a: long rains $\chi^2=3581.11$, $df=4$, $P<0.001$; short rains $\chi^2=3739.60$, $df=4$, $P<0.001$). Furthermore, the interaction between fertilizer treatments and growth stages was significant (Embu: long rains $\chi^2=725.65$, $df=24$, $P<0.001$; short rains $\chi^2=445.74$, $df=24$, $P<0.001$; Murang'a: long rains $\chi^2=405.86$, $df=24$, $P<0.001$; short rains $\chi^2=309.92$, $df=24$, $P<0.001$). Across both seasons, inorganic fertilizer consistently produced kale plants with the largest stem diameter in both Embu and Murang'a (Table 5). Among BSFFF treatments, plots amended with 150 Kg N ha⁻¹ BSFFF had the largest stem diameter in Embu across both season, while in Murang'a plots amended with 200 Kg N ha⁻¹ BSFFF consistently produced the largest stem diameter (Table 5). At twelve weeks after planting, 150 Kg N ha⁻¹ BSFFF supported the greatest stem diameter in Embu, whereas in Murang'a, the 200 Kg N ha⁻¹ BSFFF treatment resulted in the largest stem diameter during both planting seasons.

3.1.5 Chlorophyll content

Leaf chlorophyll content varied significantly due to different fertilizer treatments across both seasons and sites. In Embu, significant differences were observed during the long rains ($\chi^2=1135.18$, $df=6$, $P<0.001$) and short rains ($\chi^2=9537$, $df=6$, $P<0.001$). In Murang'a similar effects were recorded (long rains $\chi^2=595.22$, $df=6$, $P<0.001$; short rains $\chi^2=409.89$, $df=6$, $P<0.001$). Significant interaction between fertilizer treatments and growth stages were observed (Embu: long rains $\chi^2=251.44$, $df=24$, $P<0.001$; short rains $\chi^2=2346.6$, $df=24$, $P<0.001$; Murang'a: long rains $\chi^2=116.35$, $df=24$, $P<0.001$; short rains $\chi^2=124.56$, $df=24$, $P<0.001$). Additionally, growth stages alone significantly influenced chlorophyll content at both sites (Embu: long rains $\chi^2=3942.32$,

$df=4$, $P<0.001$; short rains $\chi^2=25987.7$, $df=4$, $P<0.001$; Murang'a: long rains $\chi^2=770.82$, $df=4$, $P<0.001$; short rains $\chi^2=827.89$, $df=4$, $P<0.001$). During both planting seasons, kales grown in plots amended with inorganic fertilizer recorded the highest chlorophyll content (Table 6). Among BSFFF treatments, higher application rates of BSFFF (100, 150 and 200 Kg N ha⁻¹) resulted in greater chlorophyll content compared to lower rates (0 and 50 Kg N ha⁻¹). In season two, 150 Kg N ha⁻¹ BSFFF produced the highest chlorophyll concentration in both Embu and Murang'a, while in Murang'a during season one 200 Kg N ha⁻¹ BSFFF recorded the highest chlorophyll content, twelve weeks after planting (Table 6).

3.2 Effects of different treatments on kale pest abundance and damage

3.2.1 Pest abundance

The number of cabbage aphids varied significantly due to different fertilizer treatments at both sites. In Embu, aphid abundance differed significantly due to fertilizer treatments (long rains: $\chi^2=135788$, $df=6$, $P<0.001$; short rains: $\chi^2=18317$, $df=6$, $P<0.001$) and growth stages (long rains: $\chi^2=89785$, $df=4$, $P<0.001$; short rains: $\chi^2=320573$, $df=4$, $P<0.001$). Significant interaction effects between fertilizer treatments and growth stages were also observed (long rains: $\chi^2=163913$, $df=24$, $P<0.001$; short rains: $\chi^2=68722$, $df=24$, $P<0.001$). In Murang'a, similar trends were recorded (fertilizer treatments: long rains: $\chi^2=4988.80$, $df=6$, $P<0.001$; short rains: $\chi^2=1771.30$, $df=6$, $P<0.001$; growth stages: long rains $\chi^2=6943.80$, $df=24$, $P<0.001$; short rains: $\chi^2=38804$, $df=24$, $P<0.001$; interactions: long rains: $\chi^2=5142.50$, $df=24$, $P<0.001$ and short rains: $\chi^2=1473.30$, $df=24$, $P<0.001$). Aphid abundance was generally higher in inorganic and control plots compared to the BSFFF and VIPPT plots (Figures 2A, B, 3A, B). Plants in inorganic fertilizer treatments had the highest aphids populations in both sites during season one and two in Embu (Figures 2A, B, 3A, B). Among the different rates of BSFFF, 100 Kg N ha⁻¹ BSFFF supported the highest number of aphids abundance in Murang'a during season one and across both sites during season two (Figures 2A, B, 3A, B). 150BSFFF and 200BSFFF consistently supported low populations of aphids across the seasons and agroecological zones (Figures 2A, B, 3A, B). Aphid populations peaked at week eight in both sites during both seasons.

The number of diamond back moth (DBM) varied significantly across fertilizer treatments, growth stages, and interaction between fertilizer treatments and growth stages. In Embu, DBM abundance was significantly influenced by fertilizer treatments (long rains: $\chi^2=1078.20$, $df=6$, $P<0.001$; short rains: $\chi^2=2723.20$, $df=6$, $P<0.001$), growth stages (long rains: $\chi^2=10901.30$, $df=4$, $P<0.001$; short rains: $\chi^2=21,914$, $df=4$, $P<0.001$), and interactions (long rains: $\chi^2=1851$, $df=24$, $P<0.001$; short rains: $\chi^2=17,358$, $df=24$, $P<0.001$). In Murang'a, similar significant effects were observed (fertilizer treatments: long rains $\chi^2=298.30$, $df=6$, $P<0.001$; short rains $\chi^2=1230.50$, $df=6$, $P<0.001$; growth stages: long rains $\chi^2=356.64$, $df=4$, $P<0.001$; short rains $\chi^2=3929.80$, $df=4$, $P<0.001$; interactions: long rains $\chi^2=141.30$, $df=24$, $P<0.001$; short rains $\chi^2=4914$, $df=24$,

TABLE 4 Leaf area (cm²) as influenced by different fertilizer treatments in vegetable intensified push-pull technology (VIPPT) in different agroecological zones in Kenya.

Season	Treatment	Embu					Murang'a				
		Weeks after planting					Weeks after planting				
		4	6	8	10	12	4	6	8	10	12
Long rains(April-August2024)	0BSFFF+ VIPPT	30.44±0.51a	32.24±1.99a	92.83±2.98b	106.5±60.93a	117.38±2.33a	5.04±0.19a	6.07±0.34a	10.84±0.31a	20.22±0.89a	31.14±0.28a
	50BSFFF+ VIPPT	25.3±1.[-82a	40.7±2.89ab	65.15±3.75a	114.52±1.26ab	135.34±1.9ab	17.97±2.61b	22.93±2.51bc	24.62±1.09b	31.18±0.17b	46.53±1.1b
	100BSFFF+VIPPT	38.66±0.19b	58.91±5.2c	121.56±6.9c	132.98±3.69cd	147.56±4.74b	26.78±1.19b	33.5±2.16c	48.11±1.07c	53.77±2.18c	63.12±1.21c
	150BSFFF+VIPPT	37.29±1.24b	54.27±2.42bc	126.06±2.01c	133.95±4.09cd	141.56±4.65b	57.42±3.6d	59.31±4.25d	59.89±2.26d	69.14±2.03d	93.59±0.44d
	200BSFFF+VIPPT	42.57±0.67b	55.16±2.92bc	151.58±4.17d	167.82±7.43e	174.3±5.48c	46.31±2.53c	57.67±4.25d	68.02±1.79e	78.64±1.46e	90.94±0.54d
	Control	37.77±1.06b	63.46±3.02c	116.37±3.8c	124.92±3.55bc	131.8±5.13ab	6.91±0.83a	11.84±1.75ab	11.08±0.74a	18.95±1.11a	27.86±0.95a
	Synthetic	104.14±2.6c	105.17±3.63d	132.72±7.76cd	150.52±2.03de	221.13±6.69d	46.13±2.05c	53.49±3.37d	64.92±2.58de	83.78±0.53e	100.72±2.05e
	DF	6	6	6	6	6	6	6	6	6	6
	F value	2202.20	298.51	33.58	29.24	332.18	557.40	337.36	1472.60	2388.40	4727.40
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Short rains (November 2024-April 2025)	0BSFFF+ VIPPT	46.37±0.91bc	57.84±0.69a	75.95±0.53a	97.37±0.23a	111.21±1.94a	4.17±0.41a	7.53±0.06a	11.73±0.58a	18.45±1.07a	31.25±1.22a
	50BSFFF+ VIPPT	42.78±0.41b	71.53±1.89b	99.4±0.88c	126.45±1.29b	151.92±0.56b	17.5±1.08b	25.65±0.82b	29.93±0.39b	36.2±1.28b	45.37±1.43b
	100BSFFF+VIPPT	46.44±0.76bc	87.29±1.5c	113.15±0.93d	145.77±4.11c	164.77±0.96c	21.2±0.87c	25.72±1.14b	30.79±1.01b	39.32±1.93b	57.51±1.62c
	150BSFFF+VIPPT	56.87±1.57d	127.33±1.34e	149.66±2.58e	181.19±2.79e	240.73±3.5e	28.95±0.44d	38.7±1.32c	51.3±2.04cd	64.74±1.46c	71.84±2.4d
	200BSFFF+VIPPT	46.65±0.53c	114.07±1.55d	146.97±1.67e	166.87±1.82d	217.68±1.68d	28.94±0.91d	25.65±0.82b	49.15±0.83c	64.52±0.49c	78.66±2.63d
	Control	31.69±0.61a	65.87±1.6b	86.58±0.9b	92.44±1.28a	108.65±1.14a	3.33±0.27a	6.89±0.26a	8.69±0.34a	13.06±0.35a	26.01±1.34a
	Synthetic	72.24±0.17e	114.15±0.6d	173.14±1.1f	214.78±2.71f	236.13±1.2e	21.07±0.69c	39.57±1.29c	54.88±0.79d	83.95±1.73d	103.76±1.16e
	DF	6	6	6	6	6	6	6	6	6	6
	F value	4176.60	2305.70	4176.60	2177	5817.50	1273.80	1239.50	2104.90	400.70	244.10
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic =inorganic fertilizer; Control=unfertilized plot. Per column, mean (± standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

TABLE 5 Stem diameter (cm) as influenced by different fertilizer treatments in vegetable intensified push-pull technology (VIPPT) in different agroecological zones in Kenya.

Season	Treatment	Embu					Murang'a				
		Weeks after planting					Weeks after planting				
		4	6	8	10	12	4	6	8	10	12
Long rains(April-august2024)	0BSFFF+ VIPPT	0.26±0.01a	0.34±0.02a	0.56±0.01a	0.65±0.02a	0.74±0.01a	0.12±0a	0.14±0.01a	0.43±0.02abc	0.57±0.01c	0.67±0.01bc
	50BSFFF+ VIPPT	0.36±0.02c	0.42±0bc	0.63±0.01ab	0.71±0.01a	0.84±0.02ab	0.16±0.02a	0.26±0.03b	0.33±0.01a	0.36±0.01a	0.52±0.01a
	100BSFFF+VIPPT	0.33±0.01bc	0.56±0.02d	0.67±0.01b	0.75±0.01ab	1±0.04bc	0.26±0.01b	0.36±0.01c	0.44±0.02bc	0.55±0.01c	0.65±0.02b
	150BSFFF+VIPPT	0.27±0.02ab	0.45±0.02c	0.64±0.01b	0.75±0.02ab	0.99±0.01bc	0.28±0.01b	0.38±0.01c	0.52±0c	0.58±0.01c	0.71±0.01c
	200BSFFF+VIPPT	0.25±0.01a	0.36±0.02ab	0.62±0.01b	0.84±0.02b	0.98±0.02bc	0.46±0.01c	0.56±0.01d	0.64±0.02d	0.68±0d	0.82±0.01d
	Control	0.34±0.02c	0.57±0.01d	0.86±0.02c	1.01±0.02c	1.04±0.05c	0.25±0.01b	0.32±0.02bc	0.36±0.02ab	0.45±0.01b	0.51±0.01a
	Synthetic	0.44±0.01d	0.65±0.01e	1.25±0.03d	1.31±0.06d	1.44±0.07d	0.43±0.01c	0.65±0.02e	0.67±0.03d	0.87±0.01e	0.97±0.02e
	DF	6	6	6	6	6	6	6	6	6	6
	F value	21.17	66.39	1282.50	433.05	200.88	669.78	107.30	44.37	347.20	179.60
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Short rains (November 2024-april 2025	0BSFFF+ VIPPT	0.46±0.02a	0.57±0ab	0.66±0.01a	0.7±0.01a	0.76±0.01a	0.22±0.01bc	0.25±0.01ab	0.31±0.01a	0.43±0.01a	0.46±0.01a
	50BSFFF+ VIPPT	0.45±0.01a	0.56±0.01a	0.66±0.01a	0.73±0.01a	0.83±0.01a	0.24±0.02bc	0.36±0.01d	0.37±0.01b	0.46±0.02a	0.56±0.01b
	100BSFFF+VIPPT	0.46±0.01b	0.63±0ab	0.88±0.01b	1.05±0.01c	1.45±0.11d	0.27±0.001c	0.33±0.01d	0.37±0.01b	0.44±0.01a	0.62±0.01c
	150BSFFF+VIPPT	0.56±0.01b	0.97±0.01d	1.21±0.05c	1.22±0.05d	1.32±0.11cd	0.26±0.01c	0.32±0.01cd	0.44±0.02c	0.54±0.01c	0.63±0.01c
	200BSFFF+VIPPT	0.47±0.02a	0.83±0.01c	0.95±0.01b	1±0.02c	1.11±0.02bc	0.44±0.02d	0.54±0.02e	0.64±0.02d	0.68±0.01b	0.78±0.01d
	Control	0.44±0.02a	0.63±0.01b	0.73±0.01a	0.850.01b	0.93±0.01ab	0.18±0ab	0.27±0.01bc	0.32±0.01ab	0.41±0a	0.46±0.01a
	Synthetic	0.53±0.01b	1.27±0.03e	13.9±0.04d	1.48±0.04e	1.74±0.02e	0.14±0.01a	0.21±0a	0.33±0.01ab	0.46±0.01a	0.66±0.01c
	DF	6	6	6	6	6	6	6	6	6	6
	F value	12.59	1735.40	748.65	713.06	215.28	323.21	455.46	580.01	428.07	109.10
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic =inorganic fertilizer; Control=unfertilized plot. Per column, mean (± standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

TABLE 6 Chlorophyll content as influenced by different fertilizer treatments in vegetable intensified push-pull technology (VIPPT) in different agroecological zones in Kenya.

Season	Treatment	Embu					Murang'a				
		Weeks after planting					Weeks after planting				
		4	6	8	10	12	4	6	8	10	12
long rains (April-august2024)	0BSFFF+ VIPPT	33.98±0.4a	42.33±0.69ab	43.37±0.3a	48.38±0.38a	49.47±0.5a	35.41±0.2a	38.73±0.46a	40.27±0.24a	43.65±0.44ab	45.14±0.06ab
	50BSFFF+VIPPT	37.9±0.58a	42.58±0.5ab	43.21±0.15a	45.42±0.51a	47.2±0.28a	35.6±0.61a	39.74±0.22ab	41.27±0.41ab	42.58±0.41a	45.19±0.48ab
	100BSFFF+VIPPT	37.11±0.35a	43.92±0.66ab	44.02±0.73ab	47.12±0.76a	48.53±0.45a	41.48±0.44c	44.54±0.31cd	44.98±0.57cd	45.17±0.56bcd	46.4±0.41bc
	150BSFFF+VIPPT	35.6±0.28a	42.89±0.39ab	43.74±0.87ab	47.61±0.49a	49.28±0.41a	39.41±0.55c	44.74±0.67d	45.88±0.37d	46.3±0.8cd	47.06±0.53bcd
	200BSFFF+VIPPT	38.38±0.42a	42.24±0.61a	43.65±0.44ab	47.41±0.06a	48.23±0.43a	38.84±0.17b	41.97±0.83bc	43.51±0.5bcd	44.92±0.44abc	47.65±0.81cd
	Control	43.07±0.47b	44.98±0.59b	47±0.47ab	49.38±0.57ab	51.44±0.42a	38.67±0.35b	41.22±0.62ab	42.55±0.39abc	43.1±0.32ab	43.58±0.17a
	Synthetic	46.94±0.91c	48.12±0.56c	48.38±0.22b	49.95±0.21b	57.22±0.28a	44.52±0.57d	45.35±0.52d	45.46±0.83d	47.29±0.2d	49.11±0.48d
	DF	6	6	6	6	6	6	6	6	6	6
	F value	260.52	80.434	95.02	10.04	417.41	56.53	22.47	18.40	12.42	14.74
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Short rains (November 2024- april 2025)	0BSFFF+ VIPPT	40.81±0.09a	43.67±0.04a	49±0.07b	50.91±0.05a	54.67±0.17b	38.74±0.48ab	43.09±0.46bc	44.3±0.54bc	44.82±0.37ab	45.76±0.16a
	50BSFFF+ VIPPT	43.44±0.22a	43.84±0.29a	47.51±0.21a	52.86±0.42bc	53.47±0.18a	37.44±0.58a	40.22±0.51b	42.4±0.95ab	44.94±0.43ab	46.7±0.48a
	100BSFFF+VIPPT	40.28±0.17a	44.76±0.14b	50.67±0.11c	54.2±0.06d	55.41±0.06c	40.09±0.66b	41.01±0.17b	42.87±0.29bc	43.8±0.46ab	45.46±0.76a
	150BSFFF+VIPPT	41.05±0.2a	46.21±0.13c	47.09±0.01a	53.26±0.09c	55.42±0.18c	42.66±0.44c	44.25±0.76c	45.54±0.74cd	48.12±0.78cd	49.67±0.59b
	200BSFFF+VIPPT	44.48±0.13c	46.76±0.14c	47.42±0.2a	53.3±0.15c	54.24±0.03b	41.22±0.65bc	44.1±0.46c	44.98±0.59bc	45.66±0.49bc	46.86±0.31a
	Control	43.73±0.21bc	48.15±0.3d	50.71±0.1c	52.35±0.11b	53.18±0.03a	36.26±0.41a	36.6±0.51a	39.84±0.33a	42.4±1.05a	44.71±0.41a
	Synthetic	50.33±0.08d	55.45±0.09e	56.19±0.02d	58.52±0.06e	59.38±0.15d	38.73±0.3ab	41.76±1.09bc	47.94±0.49d	49.41±0.35d	50.33±0.49b
	DF	6	6	6	6	6	6	6	6	6	6
	F value	2399.20	2958.50	3068.20	1055	1486.40	17.99	18.27	18.48	15.86	18.91
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic =inorganic fertilizer; Control=unfertilized plot. Per column, mean (± standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

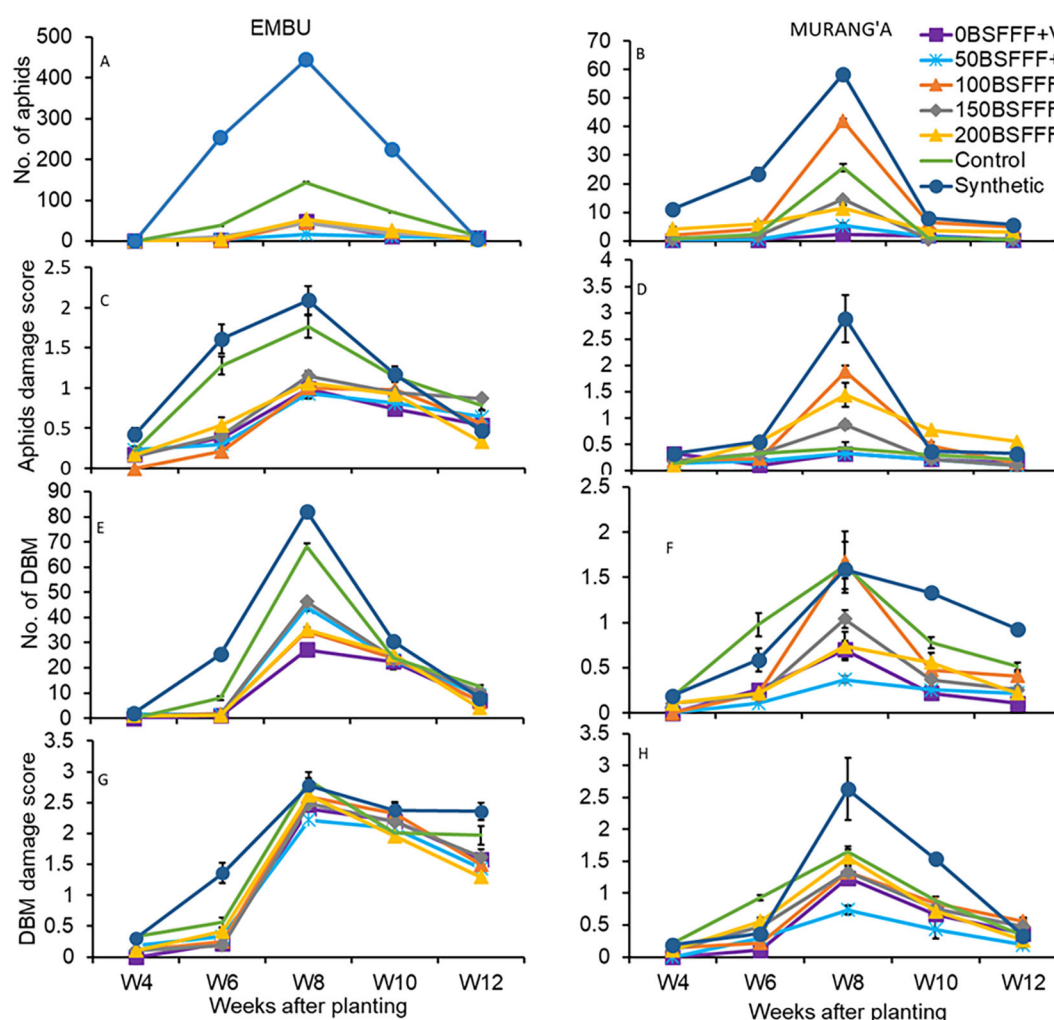


FIGURE 2

Effects of different fertilizer treatments on aphid populations (A, B), damage levels (C, D), diamondback moth (DBM) populations (E, F), DBM damage levels (G, H) on kale in the first cropping season long rains (April –August 2024) in Embu and Murang'a. OBSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic=inorganic fertilizer; Control=unfertilized plot. Per column, mean ($\pm$ standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

$P < 0.001$). Plots amended with synthetic fertilizer showed the highest DBM infestations in both seasons at Embu, and during season one in Murang'a (Figures 2E–F, 3E). In Murang'a during season one, control plots also recorded high infestations (Figure 2F). Among BSFFF treatments, 150 and 100 Kg N ha⁻¹ had the highest DBM infestations in both sites during season one, and in Murang'a during season two. DBM populations also peaked at week eight across both sites and seasons.

3.2.2 Pests damage scores

The intensity of aphid damage varied significantly across growth stages at both sites. In Embu, damage severity differed significantly due to different fertilizer treatments (long rains: $\chi^2 = 300.44$, $df = 6$, $P < 0.001$ and short rains: $\chi^2 = 5461.40$, $df = 6$, $P < 0.001$) and growth stages (long rains: $\chi^2 = 1433.07$, $df = 4$, $P < 0.001$ and short rains: $\chi^2 = 15593.00$, $df = 4$, $P < 0.001$). Significant interaction effects between fertilizer treatments and growth stages

were also observed (long rains: $\chi^2 = 424.06$, $df = 24$, $P < 0.001$; short rains: $\chi^2 = 4601.3$, $df = 24$, $P < 0.001$). In Murang'a, similar results were obtained (fertilizer treatments: long rains: $\chi^2 = 228.43$, $df = 6$, $P < 0.001$; short rains: $\chi^2 = 30987$, $df = 6$, $P < 0.001$); growth stages: long rains $\chi^2 = 471.82$, $df = 4$, $P < 0.001$; short rains: $\chi^2 = 130,671$, $df = 4$, $P < 0.001$; interactions: long rains $\chi^2 = 387.58$, $df = 24$, $P < 0.001$; short rains: $\chi^2 = 24594$, $df = 24$, $P < 0.001$). Plots amended with inorganic fertilizer showed the highest severity of aphid infestation during season one in both sites and during season two in Murang'a (Figures 2C, D, 3D). At Embu, however, control plots recorded the highest severity in season two (Figure 3C). Among BSFFF treatments, 100 Kg N ha⁻¹ BSFFF consistently resulted in the most severe aphid infestations across both seasons compared to other BSFFF rates (Figures 2C, D, 3C, D).

The intensity of diamond back moth damage varied significantly across growth stages, fertilizer treatments, and their interactions. In Embu, DBM severity differed significantly with

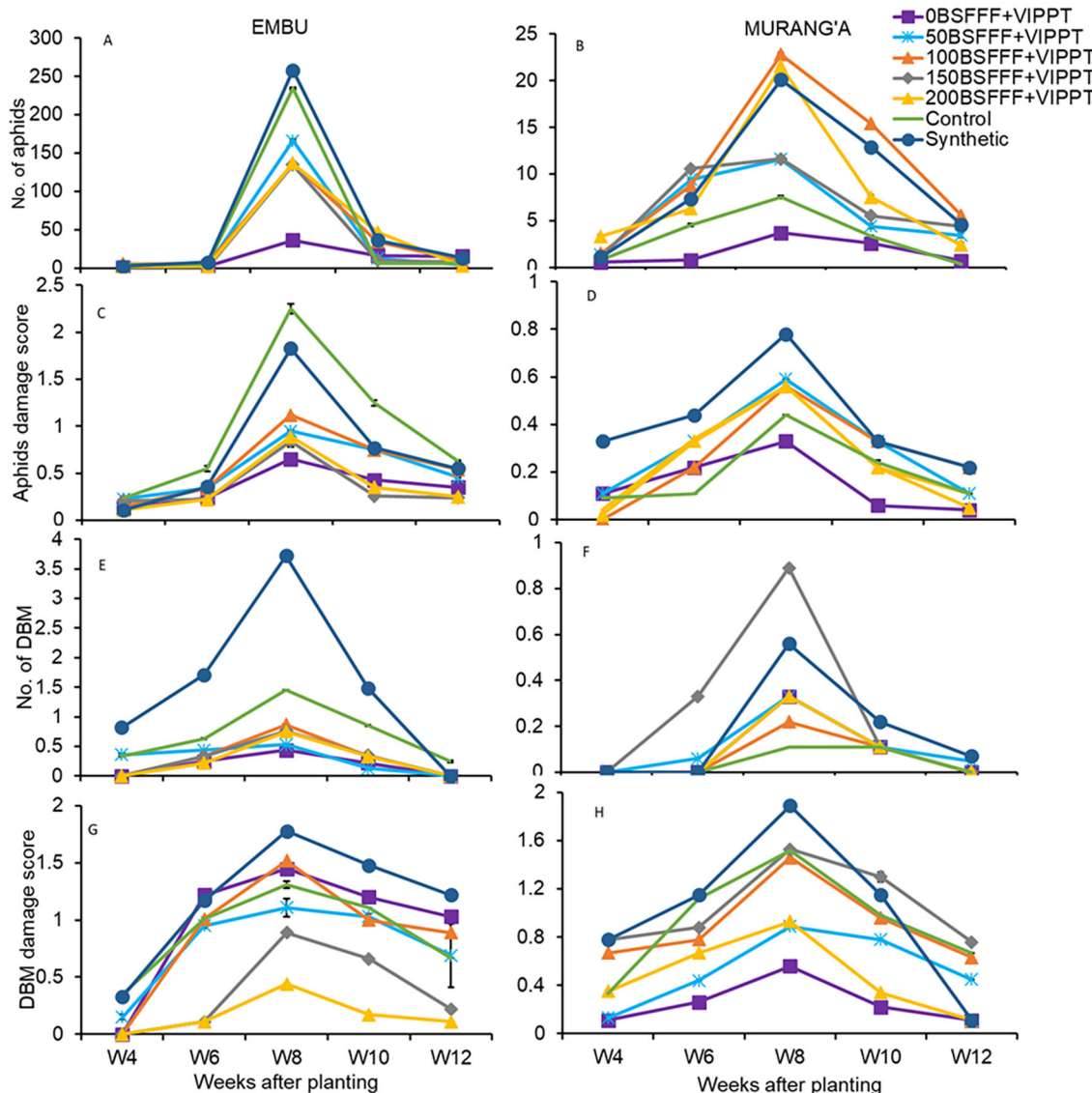


FIGURE 3

Effects of different fertilizer treatments on aphid populations (A, B), damage levels (C, D), diamondback moth (DBM) populations (E, F), DBM damage levels (G, H) on kale in the second cropping season short rains (November 2024 – April 2025) in Embu and Murang'a. 0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic=inorganic fertilizer; Control=unfertilized plot. Per column, mean ($\pm$ standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

fertilizer treatments (long rains: $\chi^2=178.78$, $df=6$, $P<0.001$; short rains: $\chi^2=1410.92$, $df=6$, $P<0.001$); growth stages (long rains: $\chi^2=3536.09$, $df=4$, $P<0.001$; short rains: $\chi^2=1690.61$, $df=4$, $P<0.001$), and interactions (long rains: $\chi^2=143.07$, $df=24$, $P<0.001$; short rains: $\chi^2=342.51$, $df=24$, $P<0.001$). In Murang'a, similar patterns were observed (fertilizer treatments: long rains: $\chi^2=124.01$, $df=6$, $P<0.001$; short rains: $\chi^2=1410.92$, $df=6$, $P<0.001$; growth stages: long rains: $\chi^2=710.63$, $df=4$, $P<0.001$; short rains: $\chi^2=1690.61$, $df=4$, $P<0.001$; interactions: long rains: $\chi^2=159.17$, $df=24$, $P<0.001$; short rains: $\chi^2=342.51$, $df=24$, $P<0.001$). Plots amended with inorganic fertilizers consistently had the highest DBM infestation severity across both seasons and sites

(Figures 2G–H, 3G–H). Among BSFFF treatments, in season two, 200 Kg N ha⁻¹ BSFFF recorded the least DBM damage in Embu throughout the growing season (Figures 3G).

3.3 Effects of different fertilizer treatments on biodiversity of natural enemies

There was significant seasonal variation in the abundance of natural enemy groups across both sites. In Embu, significant differences were observed for coleopterans ($\chi^2=10.79$, $df=1$, $P<0.01$), Araneae ($\chi^2=106.41$, $df=1$, $P<0.001$), hemipterans

($\chi^2=92.38$, $df=1$, $P<0.001$), hymenopterans ($\chi^2=133.36$, $df=1$, $P<0.001$), and neuropterans ($\chi^2=5.38$, $df=1$, $P=0.05$). In Murang'a, similar significant variation was observed for araneae ($\chi^2=147.74$, $df=1$, $P<0.001$), hemipterans ($\chi^2=53.68$, $df=1$, $P<0.001$), and neuropterans ($\chi^2=240.14$, $df=1$, $P<0.001$), while coleopterans ($\chi^2=26.41$, $df=1$, $P<0.001$) also varied significantly. Dipterans (hoverflies) varied significantly in Embu ($\chi^2=92.48$, $df=1$, $P<0.001$) but not in Murang'a ($\chi^2=1.05$, $df=1$, $P=0.30$). Fertilizer treatments significantly influenced coleopteran abundance in Embu ($\chi^2=54.45$, $df=6$, $P=0.01$) but not in Murang'a ($\chi^2=11.64$, $df=6$, $P=0.10$) (Figures 4A–D).

Generally natural enemies across all evaluated orders were more abundant in the plots treated with BSFFF and VIPPT compared to control and synthetic fertilizer treatments (Figures 4A–D). In Embu, coleopterans were most abundant group, followed by spiders (araneae) and hemipterans, while in Murang'a, araneae were most abundant, followed by coleopterans and hemipterans (Figures 4A–D). Plots amended with 200BSFFF Kg N ha⁻¹ consistently supported the highest abundance of natural enemies: Embu: Coleoptera (4% and 94% higher), Hemiptera (17% and 97% higher), and Diptera (2% and 100% higher) compared to 150 Kg N ha⁻¹ BSFFF and control or inorganic fertilizer treatments in Embu and Coleoptera (35% and 97% higher), Hemiptera (1% and 98% higher), and Diptera (9% and 100% higher) compared to 0 Kg N ha⁻¹ BSFFF and 150 Kg N ha⁻¹ BSFFF fertilizer treatments in Murang'a.

3.4 Effects of different fertilizer treatments on kale yield

3.4.1 Effects of different fertilizer treatments on fresh and dry weight of kales

The total weight of the marketable of kales varied significantly due to different fertilizer treatments during both planting seasons in both sites. In Embu, significant differences were observed during the long rains ($\chi^2=1212.80$ $df=6$ $P<0.001$) and short rains ($\chi^2=1529$ $df=6$ $P<0.001$) (Figures 5A, C). In Murang'a, similar significant effects were found (long rains: $\chi^2=1214$ $df=6$ $P<0.001$; short rains: $\chi^2=6351.5$ $df=6$ $P<0.001$) (Figures 5B, D). In Embu, yields were between 207–766% higher (season one) and 49–433% higher (season two). In Murang'a, inorganic fertilizer plots yielded 13–92% more than BSFFF treatments during season two. Among BSFFF treatments, 200 Kg N ha⁻¹ BSFFF produced the highest weight yields across both sites. In Embu, this rate increased marketable yield by 50% and 65% compared to 50 and 0 Kg N ha⁻¹ BSFFF during the long rains, and by 13% and 78% compared to 150 and 0 Kg N ha⁻¹ BSFFF during the short rains. In Murang'a, the application of 200 Kg N ha⁻¹ BSFFF increased kale yield by 86% during the short rains compared to push–pull plots without BSFFF (0 Kg N ha⁻¹).

Fertilizer treatments also significantly influenced kale dry weight at both sites and across both seasons. In Embu, significant effects were observed during the long rains ($\chi^2=1214.0$, $df=6$, $P<0.001$) and short rains ($\chi^2=89.95$, $df=6$, $P<0.001$). In Murang'a,

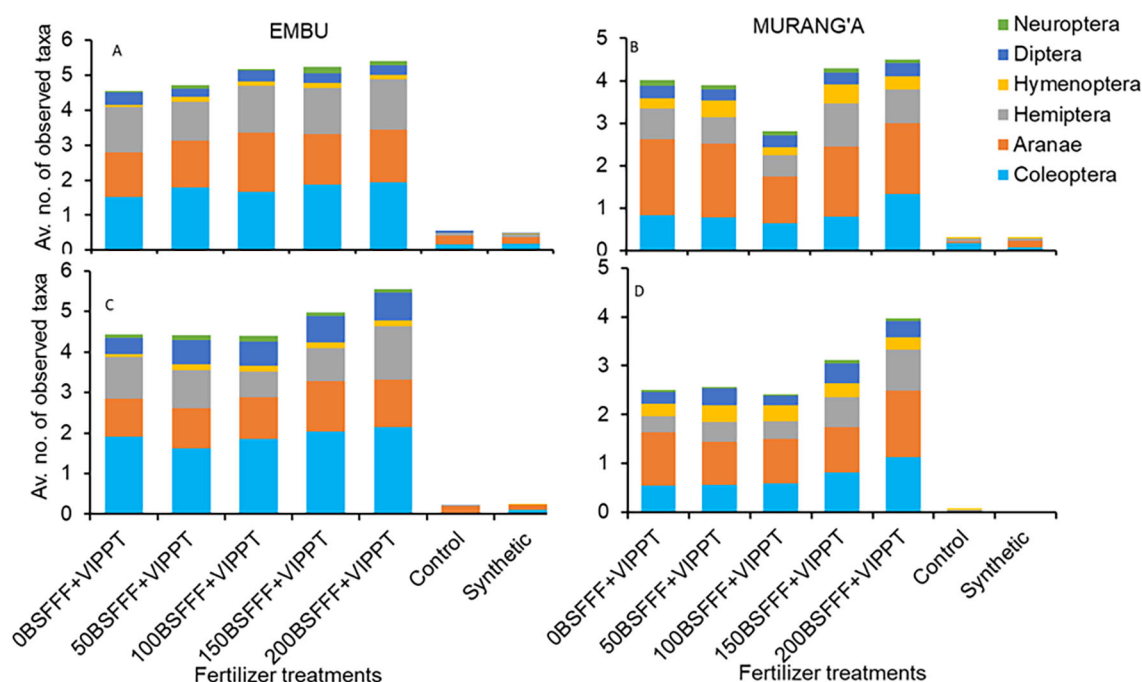


FIGURE 4

Effects of different fertilizer treatments on abundance of natural enemies in Embu and Murang'a sites (A, B) during season one and season two (C, D). 0BSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer respectively; synthetic=inorganic fertilizer; Control=unfertilized plot. Per column, mean ($\pm$ standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

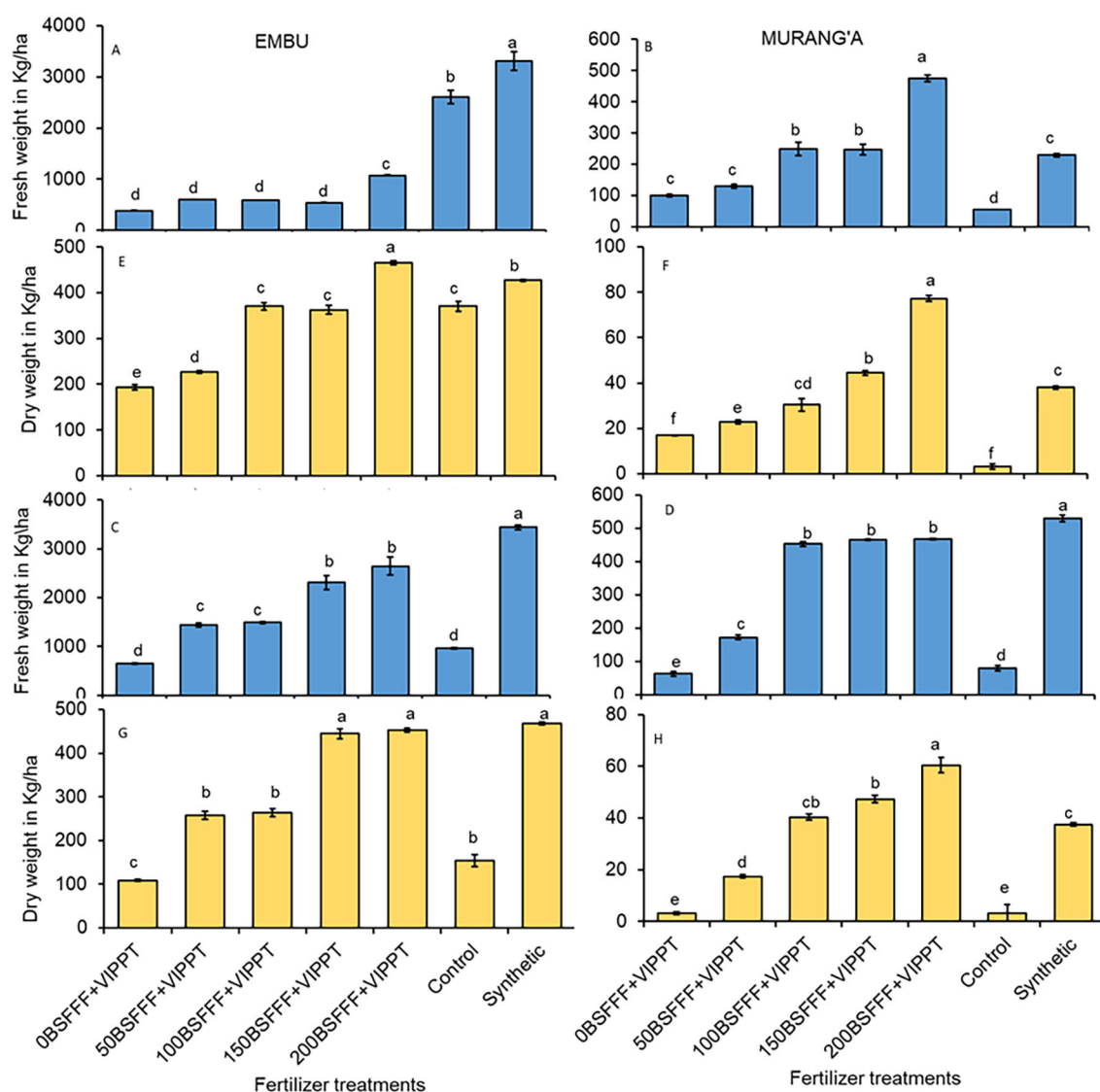


FIGURE 5

Effects of different fertilizer treatments on fresh weight and dry weights of kales in Embu and Murang'a (A, B, E, F) during season one long rains (April–August 2024) and two short rains (November 2024–April 2025) (C, D, G, H). OBSFFF, 50 BSFFF, 100 BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0,50,100,150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic =inorganic fertilizer; Control=unfertilized plot. Per column, mean (± standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

similar effects were found (long rains: $\chi^2=308.64$, $df=6$, $P<0.001$; short rains: $\chi^2=1397.60$, $df=6$, $P<0.001$) (Figure 5). Generally, the treatments with the highest fresh weights recorded the highest dry weights. In both sites, plots amended with inorganic fertilizer and 200 Kg N ha⁻¹ BSFFF consistently produced the greatest dry weight across the two planting seasons (Figure 5).

3.4.2 Effects of different fertilizer treatments on the weight of non-marketable kales

The weight of the non-marketable kales leaves (damaged or diseased) varied significantly across fertilizer treatments in both sites during the two planting seasons. In Embu, significant effects were observed during the long rains ($\chi^2=35.83$ $df=6$ $P<0.001$) and short rains ($\chi^2=44$ $df=6$ $P<0.001$) (Figures 6A, C). In Murang'a, similar

results were recorded (long rains: $\chi^2=2832$ $df=6$ $P<0.001$; short rains: $\chi^2=3291.40$ $df=6$ $P<0.001$) (Figures 6B, D). Across both sites, plots amended with inorganic fertilizer consistently produced the highest numbers of non-marketable leaves compared to other treatments (Figure 6). In Embu, inorganic fertilizer treatments resulted in 15–29% more unmarketable leaves than control and VIPPT plots (0 Kg N ha⁻¹ BSFFF) during season one, and 50–400% more than 100 and 0 Kg N ha⁻¹ BSFFF during season two. In Murang'a, inorganic fertilizer increased non-marketable yields by 87–100% compared to 150 and 0 Kg N ha⁻¹ BSFFF in season one, and by 39–131% compared to 100 and 0 Kg N ha⁻¹ BSFFF in season two. Among BSFFF treatments, 200 Kg N ha⁻¹ BSFFF produced the least number of non-marketable leaves compared to marketable leaves by 13% and 15% in Embu and Murang'a respectively during the two seasons. During season two,

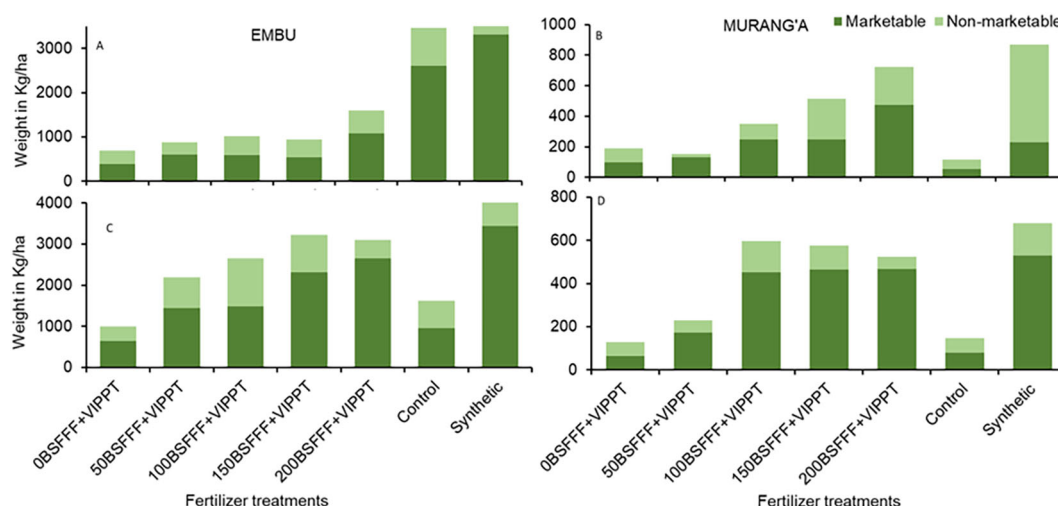


FIGURE 6

Effects of different fertilizer treatments on marketable and non-marketable leaves of kales in Embu and Murang'a (A, B) during season one long rains (April–August 2024) and season two short rains (November 2024–April 2025) (C, D). 0BSFFF, 50BSFFF, 100BSFFF, 150BSFFF and 200BSFFF= application rates equivalent to 0, 50, 100, 150 and 200 kg N ha⁻¹ of black soldier fly frass fertilizer; synthetic=inorganic fertilizer; Control=unfertilized plot. Per column, mean ($\pm$ standard error) followed by the same letter(s) are not significantly different at $P \leq 0.05$.

however, 100 Kg N ha⁻¹ BSFFF plots had the highest non-marketable yield (50–400% more than 150 and 0 Kg N ha⁻¹ BSFFF). In Murang'a, 150 Kg N ha⁻¹ BSFFF supported the highest non-marketable yield in season one (9–100% more than 200 and 0 Kg N ha⁻¹ BSFFF), whereas in season two, 100 Kg N ha⁻¹ BSFFF had the highest values (31–125% higher than 150 and 0 Kg N ha⁻¹ BSFFF).

4 Discussion

4.1 Growth and yield of kales grown under vegetable integrated push-pull system amended with BSF frass fertilizer

Kales planted in the plots amended with higher organic fertilizer rates (150 and 200 Kg N ha⁻¹ BSFFF) performed better than lower rates and unamended soil (control) especially in Murang'a across growth parameters. This aligns with earlier studies showing that BSFFF enhances crop growth and yield in various vegetables, broccoli (Kagehi et al., 2025) kale, French beans and tomatoes (Romano et al., 2023; Anyega et al., 2021), lettuce (Dzepe et al., 2022), chili and shallots (Quilliam et al., 2020) and brassicas (Kagata and Ohgushi, 2012). Our study also complements past studies that have also reported taller plants and higher chlorophyll content in crops grown using BSFFF (Klammsteiner et al., 2020; Quilliam et al., 2020). In concurrence with our current study, other studies have reported increased leaf area and stem diameter in plants grown in soil amended with BSFFF (Chepkorir et al., 2024; Chia et al., 2025). The BSFFF contains essential nutrients, both the macro- and micronutrients (Beesigamukama et al., 2022; Gärtling and Schulz, 2022) which increases nutrient availability, enhances release of nutrients at a slow consistent rate and improves soil structure due to high organic matter which in turn protects soil against agents of

erosion such as wind and water. This could have contributed to faster growth rate exhibited in our study (Han et al., 2016). Frass from other insects such as cricket and meal worm has been shown to improve the physical and chemical characteristics of soil to promote the growth of crops such as spring onions (Ogaji et al., 2022; Chia et al., 2024). The comparable performance of frass fertilizer and mineral fertilizer in terms of number of leaves and stem diameter in our study especially those treated with higher rates also supports previous reports by Klammsteiner et al., 2020. Higher growth rates reported in different BSFFF treatments could be attributed to a variety of microorganisms in frass which increases microbial biomass, diversity and activity in the soil leading to higher nutrient availability to plants since these microorganisms are capable of increasing the rates of nitrogen mineralization (Frost and Hunter, 2007). BSFFF increases nitrogen use efficiency which results to faster growth and high yield (Beesigamukama et al., 2020). It has been shown to increase growth rate, amount of the organic matter in the soil, electrical conductivity of the soil and suppress plant diseases (Zahn, 2017). The integration of the organic fertilizer increases nutrient supply and the intercropping in the VIPPT supplied sufficient nutrients that in turn affect plant growth, quality and productivity (Sherwood and Uphoff, 2000; Beesigamukama et al., 2020). As reported in earlier studies, desmodium used as our push plant fixes atmospheric nitrogen, improves soil organic matter which leads to improved soil nutrient availability and better soil moisture retention, creating a more favorable environment for crop growth (Chepchirchir et al., 2018; Mutyambai et al., 2024).

In this study, we observed a higher quality and yield of kale in the VIPPT plots compared to the control plots, with notable results in Murang'a. This improvement in the number and weight of marketable kale leaves is likely due to reduced pest and disease pressure in the VIPPT plots relative to the control and synthetic fertilizer treatments. Additionally, the increased vegetable yield in

VIPPT plots can be attributed to the multiple benefits provided by this technology. The inclusion of desmodium contributes to improved soil fertility, acts as a live mulch that conserves soil moisture, and provides ground cover that suppresses weed growth. These advantages complement the well-documented roles of push-pull technology (PPT) in managing pests and striga weed in cereal production (Khan et al., 2011). Our results show that integration of BSFFF and push-pull significantly increased kale yield compared to push-pull without fertilizer, and the kale yield increased with BSFFF application rates. This implies that intensification push-pull should be accompanied by extra nutrient inputs to cater for the increased nutrient demand by crops added in the push-pull system and maintain soil health. This is critical especially in mixed farms where farmers harvest companion crops (desmodium and either brachiaria or napier grass) for use as animal feeds. The circularity of such systems is challenged by the poor manure management practices in Africa, whereby most farmers do not return animal manure to the farm (Ebanyat et al., 2010; Ndambi et al., 2019). Although the highest kale yield was obtained at highest BSFFF rate, it is anticipated that continued application of frass fertilizer will reduce the need for higher application due to residual benefits of BSFFF as an organic fertilizer (Beesigamukama et al., 2023). The inorganic fertilizer performed better than the BSFFF which is contrarily to previous studies (Beesigamukama et al., 2020; Anyega et al., 2021). This could be attributed to the lower rates of BSFFF used compared to the rates used for kales by Anyega et al., 2021 who used 371 Kg N ha⁻¹. The influence of the higher rates and the inorganic fertilizer was comparable, indicating a synergy between BSFFF and VIPPT. Control plots in Embu outperformed all the different rates of BSFFF unlike in Murang'a. This could be attributed to the previous soil amendments that the soil had been subjected to since the soil was not virgin like the case for Murang'a. It could further be also attributed to the results showing levels of different nutrients from initial soil analysis as presented in (Table 1). Across the two agroecological zones represented by the two sites, Embu had higher yield compared to Murang'a. This could be attributed to the differences in soil physiochemical properties and weather patterns especially rainfall and temperature during the planting seasons. Embu exhibited higher rainfall and higher temperatures compared to Murang'a providing a conducive environment for plant growth (Figure 1). The soils in Embu were also fertile compared to the soils in Murang'a (Table 1). Amidst all these factors, 200 Kg N ha⁻¹ BSFFF, performed well compared to the other rates. Our This study therefore, recommends the application rate of 200 Kg N ha⁻¹ BSFFF in push pull systems since it will boost crop growth and yield and reduce pest incidence.

4.2 Effects of black soldier fly frass and inorganic fertilizers on the abundance of pests and damage severity in a vegetable integrated push-pull system

Our results show that aphids and diamondback moth were lower in the VIPPT and BSFFF treated plots compared to the plots

amended with inorganic fertilizer and the unamended soil (control) especially in Embu. These findings corroborate other studies that reported the efficacy of VIPPT in reducing the populations of aphids and DBM, the major pests of kale production, together with grasshoppers (Ben-Issa et al., 2017; Chidawanyika et al., 2025). The reduction in the pest densities and their damage levels could be attributed to several factors including the ability of insect frass fertilizer to improve tolerance to biotic stresses such as pests and diseases through increased expression of defense genes (Barragan-Fonseca et al., 2022; Blakstad et al., 2023; Mutyambai et al., 2025). Both frass itself and extracts derived from it have been described as products with antimicrobial properties, due to the presence of antibacterial, antifungal, and nematicidal compounds (Zunzunegui et al., 2025). Chitin from dead insects' exoskeleton which is contained in the insect frass fertilizer naturally suppress many plant diseases by inducing immune responses in plants (Lagat et al., 2021; Anedo et al., 2024; Kisaakye et al., 2024).

Frass also contains growth hormones and beneficial microbes such as cytokinins and gibberellins hence its application increases the plants ability to suppress plant pests Barragán-Fonseca et al. (2022) and Ferruzca-Campos et al. (2023) and diseases (Lagat et al., 2021; Kemboi et al., 2022; Jiang et al., 2025). Furthermore, long term benefits such as increased soil organic matter, soil structure and beneficial soil microbiome associated with such VIPPT and BSFFF contribute to improved plant vigor and tolerance to pests and diseases (Ramesh et al., 2005; Atijegbe et al., 2014).

It has also been demonstrated that frass from other insects such as mealworm has a significant effect on the soil, raising the availability of nitrogen and possibly enhancing plant development and resistance to diseases and pests (Houben et al., 2020). Additionally, the black soldier fly frass may promote growth and nutrient uptake in crops and raise chlorophyll concentration, which further supports plant vigor under stress such as drought (Beesigamukama et al., 2020; Fuertes-mendiz et al., 2023; Sawinska et al., 2024). This suggests that frass may promote a more beneficial soil microbiome for plant stress tolerance. Frass there acts as immune stimulant and defense primer in plants (Blakstad et al., 2023). Insect frass has been described as an effective vehicle for entomopathogens present in the frass of the gypsy moth (*Lymantria dispar*) and capable of killing the insect pest (Goertz and Hoch, 2011; Zunzunegui et al., 2025). The findings are also in line with studies that have linked this benefits of frass to decreases pest infestation of Dbm (Chia et al., 2024). All this attributes from frass fertilizer could be attributed to the low pest population and damages in the VIPPT and BSFFF plots.

Our study noted less infestation levels of DBM and aphids in the VIPPT plots compared to the non-push pull plots (inorganic fertilizer treatment and control). This could be attributed to volatiles such as (E)-4,8-dimethyl-1,3,7-non-atratriene (DMNT) that are constitutively released from the desmodium intercrop and enhance pest repellency (Khan et al., 2000). Furthermore, the increased production of toxic defensive metabolites, such as benzoxazinoids by push-pull companion crops reinforces the push-effect, as well as contributing directly to plant resistance (Mutyambai et al., 2019). The reduction in infestation levels in

VIPPT plots could also be attributed to disruption of the olfactory-guided location of hosts using non-host plants as reported by previous studies (Broad, 2008; Mutua et al., 2024). Additionally, there is disruption of the lifecycles using non-host plants of the pests such as DBM (Asare-Bediako et al., 2010). Furthermore, vegetation diversification created by intercropping with other crops contributes to reduced aphids infestation due to change in pests perceivable color cues (Mutiga et al., 2010). Diversified cropping and companion cropping systems in our study brought about habitat complexity that are associated with increased pest suppression that lead to lower crop damage levels as reported in other studies (Letourneau et al., 2011; Chidawanyika et al., 2025). Conditioning soil through push pull cropping system has been also been reported to not only increase the level of nutraceutical compounds such as glucosinolates but also boost the defense mechanism of crops such as kales and maize (Mutiyambai et al., 2025; Opio et al., 2025).

4.3 Effects of different fertilizer treatments on biodiversity of the natural enemies in a vegetable integrated push-pull system

We reported higher number of natural enemies in the VIPPT and BSFFF plots compared to the control and synthetic fertilizer treatments. These findings are in line with previous studies where different push and pull plants have been used to attract natural enemies through various mechanism hence reducing pest population in the main crops (Asare-Bediako et al., 2010; Chidawanyika et al., 2025). This could be a result of volatiles from insect frass which have shown a great potential for controlling insect pests in plants, these volatiles include pheromones from pest insects present in their frass, which act as powerful attractants for entomopathogens, such as nematodes and parasitoids of other pests such as *Tuta absoluta* and fall army worm (Desneux et al., 2009; Ayelo et al., 2022; Zunzunegui et al., 2025). The higher diversity of natural enemies observed in the VIPPT plots could be as a result of volatiles, such as (E)-4,8-dimethyl-1,3,7-nonatriene (DMNT), released by the desmodium intercrops that attracted natural enemies (Khan et al., 1997) and enhanced natural enemy diversity by volatile mediated attraction (Khan et al., 1997; Mutua et al., 2024).

Companion or trap plants used in our study also produced floral resources, which is associated with enhanced longevity of parasitoids, reproduction of predatory insects hence push-pull approach increases functional agrobiodiversity, providing resources such as nectar or shelter from companion plants, which supports natural enemy populations and increases their abundance and richness in vegetable crops as reported in previous studies (Amaral et al., 2013; Haro et al., 2018; da Silva et al., 2022). The VIPPT companion plants (brachiaria grass and desmodium) used in our study emit compounds that are attractive to the parasitic wasps and significantly improves their foraging activities as

reported by Khan et al. (1997 and 2000). In response to herbivore attack as previously reported, plants produced semiochemicals that can be important in indirect effects in plant defense by attracting the pests' natural enemies (Mutiyambai et al., 2014). These mechanisms could also be attributed to higher number of natural enemies in the VIPPT plots (Khan et al., 2008). The higher diversity observed in the VIPPT plots is associated with the desmodiums' ability to produce semiochemicals such as pheromones that act as a kairomone attracting aphid natural enemies, thereby enhancing their foraging efficiency near the crop as previously reported (Cook et al., 2007; Murage et al., 2015).

Our study aligns with the findings of Schmidt et al. (2004), who reported that desmodium, used as a cover crop (mulch), increased the abundance of ground-dwelling spiders and reduced infestations of aphids and diamondback moth (DBM). This suggests that enriching the soil surface with litter and cover crops can enhance pest control. Therefore, conserving or applying crop residues to arable fields presents a promising cultural practice for strengthening natural pest regulation. Diversified planting offered in our study disrupts the visual and olfactory cues aphids use, while enhancing search efficiency for natural enemies since they often prefer complex plant structures, which trap crops can provide, diversified cropping systems like push pull therefore enhance natural enemies populations as also reported by previous studies (Letourneau et al., 2011). The insect frass fertilizer has also been reported to enhance the release of attractive volatiles for natural enemies (Barragán-Fonseca et al., 2022). However, in future it will be necessary to investigate the volatiles released by vegetables grown in soil amended with BSFFF under a vegetable integrated push-pull system to elucidate the mechanisms of pest suppression and natural enemy abundance.

5 Conclusion

Our study has demonstrated that integration of BSFFF and VIPPT improves kale growth, suppression pest infestation and damage severity, enhances the diversity and abundance of pests' natural enemies and increases the overall yield and quality of kales under these two integrated technologies. Additionally, different BSFFF application rates in VIPPT have been shown to have different impact on vegetable growth, pest infestation and damage, diversity and abundance of pests' natural enemies and the overall yield and quality. Of the different BSFFF application rates, 200 Kg N ha⁻¹ provided better effects in terms of kale growth performance, pest suppression, biodiversity conservation and the overall kale quality and yield. The integrated use of BSFFF and VIPPT creates a regenerative agroecological system that improves crop quality, suppresses pests and increases yields sustainably. Future studies should investigate the spatial-temporal effects of integration of these two technologies including mid-long term impacts on crop yield, pest management, agrobiodiversity and soil health to generate recommendations for scaling.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

PK: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. DB: Formal Analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. JW: Methodology, Supervision, Validation, Writing – review & editing. BS: Methodology, Validation, Visualization, Writing – review & editing. CT: Data curation, Resources, Validation, Visualization, Writing – review & editing. FC: Validation, Visualization, Writing – review & editing. SS: Conceptualization, Funding acquisition, Resources, Validation, Writing – review & editing. DM: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Supervision, Visualization, Writing – original draft.

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