Performance of black soldier fly frass fertiliser on maize (*Zea mays* L.) growth, yield, nutritional quality, and economic returns

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Abstract

Although the black soldier fly frass fertiliser (BSFFF) is globally recognised as a promising and potential high-quality organic fertiliser, there is inadequate information on its impact on the growth performance and nutritional status of maize. Furthermore, no information exist on their combination with mineral fertiliser (NPK) as well as economic impact on maize production. This study evaluated the comparative impact of BSFFF, NPK and commercial organic fertiliser (Evergrow®) on growth, nitrogen use efficiency, yield, nutritional quality, and profitability of maize under greenhouse conditions. The treatments included: (1) sole application of BSFFF, conventional compost of brewers' spent grain (BSG), Evergrow, and NPK at rates equivalent to 100 kg nitrogen (N) per hectare; (2) BSFFF and BSG combined with NPK so that each fertiliser supplies 50% of the N required; and (3) the control (unamended soil). Our findings revealed that BSFFF increased maize grain yield at higher rates: 2-25, 25-113 and 153-212% than NPK, BSG and Evergrow, respectively. Similarly, the BSF frass application led to higher maize growth and yield than the control treatment. The agronomic N use efficiency of maize grown using BSFFF was 2 and 3 times higher compared to that of BSG and Evergrow, respectively. Maize grown using BSFFF and NPK had higher crude protein and crude fibre content compared to the other treatments. The net income generated from the commercialisation of maize grown using a combination of BSFFF and NPK was 2, 163 and 173% higher than those achieved using sole NPK, mixture of BSG and NPK, and sole BSFFF, respectively. Our results imply that developing and promoting BSFFF alone or in integration with NPK can enhance the food security and livelihoods of smallholders, while safeguarding planetary health.

Keywords: insect frass fertiliser, soil fertility, grain yield, grain nutrient quality, economic benefit

1. Introduction

The black soldier fly (BSF) (*Hermetia illucens*, L) is an efficient recycler of organic wastes into nutrient-rich organic fertiliser for crop production and soil health management (Beesigamukama *et al.*, 2021; Lalander *et al.*, 2015). Due to their high waste degradation efficiency (65-78%) (Diener *et al.*, 2011; Li *et al.*, 2011), the BSF larvae have been reported to shorten the compost maturity period to 5 weeks, compared to 8-24 weeks of conventional composting methods (Beesigamukama *et al.*, 2020a, 2021). Furthermore,

the BSF larvae can drastically reduce pathogens (Erickson *et al.*, 2004; Klammsteiner *et al.*, 2020; Lalander *et al.*, 2015) and chemical contaminants (Lalander *et al.*, 2016) contained in organic waste to levels permissible for field application of the resultant organic fertiliser product (Bernal *et al.*, 2009).

The BSF frass can be integrated as fertiliser for production of crops such as maize (*Zea mays* L.), the most important crop worldwide (Jain, 2014; Sandhu *et al.*, 2007) grown for food (Rouf *et al.*, 2016; Shah *et al.*, 2015), feed (Adiaha, 2016), pharmaceutical (Kumar and Narayan, 2013), herbal

and fuel production (Abdulrahman and Kolawole, 2006). In sub-Saharan Africa (SSA), maize is a strategic food security crop for more than 300 million Africans, grown on 25 million hectares (Badu-Apraku, 2017). However, maize's food security and economic contribution are challenged by poor soil fertility linked to nutrient depletion, limited fertiliser use, poor management of pests, climate change, and socioeconomic and institutional hurdles (AGRA, 2014; De Groote *et al.*, 2010; Gibbon *et al.*, 2007; Kassie *et al.*, 2015; Stewart *et al.* 2020). Studies indicate that low soil fertility, low soil nitrogen, and drought reduce maize yields in Africa by 62, 76 and 54%, respectively (Gibbon *et al.*, 2007). This is a huge loss given the number of food-insecure people in Africa, 332 million in 2016 (FAO *et al.*, 2017). For optimal maize growth, nitrogen (N) must be sufficient throughout the growing period because it plays a significant role in key physiological processes such as the synthesis of chloroplasts, proteins, amino acids, and cell division (Fageria, 2001). Inorganic fertilisers' adoption is low in SSA, mainly due to high prices and limited access to credit. Further, there is little use of organic fertilisers due to competing uses for feed and fuel (Ndambi *et al.*, 2019). Therefore, an alternative source of fertiliser is crucial to enhance the resilience and food security of SSA. The insect frass obtained as a by-product of BSF larvae production can play a vital role in mitigating soil nutrient deficiency in SSA, thereby increasing agricultural productivity and food security.

Previous studies have demonstrated the potential of BSF frass for improving plant health, crop yield, and soil fertility (Alattar *et al.*, 2016; Beesigamukama *et al.*, 2020b,c; Green and Popa, 2012; Quilliam *et al.*, 2020; Zahn, 2017). However, there is inadequate information on BSF frass fertiliser impact on the growth performance and nutritional status of maize. Furthermore, no information exist on their combination with mineral fertiliser (NPK) as well as economic impact on maize production. This study evaluated the comparative impact of: (1) sole application of black soldier fly frass fertiliser (BSFFF), conventional compost of brewers' spent grain (BSG), commercial organic fertiliser (Evergrow®), and NPK at rates equivalent to 100 kg nitrogen (N) per hectare; (2) BSFFF and BSG combined with NPK so that each fertiliser supplies 50% of the N required; and (3) the control (unamended soil) on the: growth, nitrogen use efficiency, yield, nutritional quality, and profitability of maize under greenhouse conditions. This is relevant to generate the necessary information for integrating BSF frass fertiliser into the existing farming practices.

2. Materials and methods

Experimental site

A greenhouse experiment was carried out at the International Centre of Insect Physiology and Ecology (*icipe*) (1°10'59" S, 36°55'34" E), Nairobi, Kenya. The soil used for

crop production during experiments was collected from *icipe* at a depth of 0-20 cm. The soil was classified as an Acric Ferralsol (Gachene and Kimaru, 2003) with loamy textural class, medium acidity, and low organic matter levels, total nitrogen, and available phosphorus. Before experiments, the soil was analysed for pH, organic carbon, and nutrient concentrations using standard laboratory methods (Okalebo *et al.*, 2002). Table 1 presents the soil analysis results.

Source of fertilisers

The study consisted of four fertilisers: BSFFF, a conventionally composted organic fertiliser, a commercial organic fertiliser (Evergrow), and mineral fertiliser (NPK 17:17:17). The Evergrow and NPK fertilisers were sourced from Sanergy Ltd and Kenya farmers' Association, respectively. The conventional compost was generated from BSG, while the BSF frass was obtained from BSF rearing at the animal rearing and quarantine unit at *icipe*. The two organic materials were composted following the procedures described below.

Brewery spent grain and BSF frass composting

The BSF larvae were reared on BSG following procedures described in Beesigamukama *et al.* (2021). After larval harvesting, the BSF frass generated was composted using the heap composting method to obtain a mature and stable organic fertiliser product, referred to as BSF frass fertiliser. Since the C/N ratios of the BSG and BSF frass were below the value recommended for efficient composting, they were amended with rice husks to achieve C/N of 25:1 (Inckel *et al.*, 2005). The amount of rice husk required to adjust the C/N ratio of BSG and BSF frass to 25:1 was calculated (Richard and Trautmann, 1996). Table 2 presents

Table 1. Properties of the soil used during experiments.

Soil parameter	Value
pH	5.80
Total nitrogen (%)	0.05
Total organic carbon (%)	0.24
Available phosphorus (mg/kg)	5.0
Potassium (me%) ¹	0.84
Calcium (me%)	2.2
Magnesium (me%)	2.77
Manganese (me%)	0.43
Copper (mg/kg)	1.00
Iron (mg/kg)	29.5
Zinc (mg/kg)	3.00
Sodium (me%)	0.28

¹ me% = milliequivalent percentage.

characteristics of raw composting substrates, composted BSF frass and BSG, and the commercial organic fertilisers.

Treatments and experimental setup

The BSFFF, BSG, Evergrow, and NPK fertiliser were applied at uniform rates equivalent to 100 kg N/ha in two sets of experiments. In the first set of treatments, 100% of the N required was supplied using sole organic fertilisers and sole NPK. These were denoted as BSFFF, BSG, and Evergrow, NPK for sole BSFFF, BSG, Evergrow, and NPK, respectively. The quantity of fertilisers required to supply the 100 kg N/ha were equivalent to 2.8, 4.1, 10 t/ha for sole BSFFF, BSG, Evergrow, respectively, and 588 kg/ha for sole NPK. In the second set of treatments, the BSFFF and BSG were combined with mineral fertiliser, whereby 50% of the N required was supplied using organic fertilisers, and the other 50% was supplied using mineral NPK fertiliser. These were denoted as BSFFF/NPK and BSG/NPK for combined BSFFF, BSG treatments, respectively. The quantity of fertilisers required to supply 50% of the N required (that is 50 kg N/ha) was equivalent to 1.4, 2.05 t/ha for BSFFF and BSG, respectively, and 294 kg/ha for NPK. In both experiments, the control treatment consisted of unamended soil.

The experiments were carried out in a greenhouse using polythene pots measuring 30 cm long, 40 cm wide, and 60 cm deep. Each polythene pot was filled with 10 kg of fresh soil, which was mixed with the different treatments. The experiments were arranged in a randomised complete block design with four replicates. Each replicate consisted of 10 pots, arranged at a spacing of 70×30 cm. Two seeds of maize variety H517 sourced from Kenya Seed Company were planted per pot. At two weeks after germination,

thinning was done to maintain one plant per pot. The organic fertilisers (BSFFF, BSG, and Evergrow) were applied one week before sowing. The NPK fertiliser was applied in two splits, at sowing (50%) and four weeks after planting (50%). During experiments, weeds were controlled by hand pulling, while a drip irrigation system was installed to cater for crop water requirements.

Maize growth, yield, and nutritional quality

Six maize plants were randomly selected and tagged from each treatment for the determination of growth parameters. Data on plant height, stem diameter, number of leaves, and chlorophyll content were collected every four weeks, from the fourth week after sowing up to the maturity stage. Plant height was measured using a tape measure, from ground level to the tip of the shoot. Maize stem diameter was measured using a vernier caliper placed at the 10 cm mark from the ground level. The number of leaves per plant was determined by hand counting, while leaf chlorophyll concentration was measured using a SPAD meter placed on the fourth fully opened leaf from the top (Yuan *et al.*, 2016).

Maize grain and stover yield data were collected at maturity by harvesting all plants per treatment. Plants were cut at ground level, and their ears threshed to determine grain weights and weight of residues using a weighing scale. Grain and stover samples were air-dried to 12.5% moisture content to determine grain and residues yields per hectare (t/ha). The grain yield from each treatment was used to calculate the economic yield produced per unit amount of nitrogen supplied from each treatment, using the agronomic nitrogen efficiency (AE_N) (Equation 1) (Baligar *et al.*, 2001).

Table 2. Characteristics of raw substrates, composted black soldier fly (BSF) frass and brewery spent grain (BSG), and the commercial organic fertiliser (Evergrow) used in experiments.

Parameter	Composting substrates			Mature and stable composts		Evergrow fertiliser
	Raw frass	Raw BSG	Rice husks	Composted BSF frass	Composted BSG	
pH	6.79	5.59	6.98	7.3	7.1	7.8
Organic carbon (%)	50.47	51.70	57.46	38.6	37.9	20
Nitrogen (%)	5.01	4.54	0.26	3.6	2.5	1.0
Phosphorus (%)	0.93	0.59	0.06	0.50	0.37	0.4
Potassium (%)	0.22	0.12	0.33	0.29	0.24	0.5
Calcium (%)	0.62	0.42	0.26	0.97	0.28	1.3
Magnesium (%)	0.28	0.21	0.12	0.10	0.15	0.2
Iron (%)	0.13	0.05	0.118	0.031	0.019	0.12
Copper (mg/kg)	21.97	12.07	56.47	25.0	15.0	100
Manganese (mg/kg)	102.23	69.17	558.67	109.0	262.0	200
Zinc (mg/kg)	180.67	107.33	85.07	182.0	167.0	850
C/N ratio	10.07	11.39	221.0	10.7	15.5	20

$$AE_N(\text{kg/kg N}) = \frac{[\text{Grain yield}_F(\text{kg/ha}) - \text{Grain yield}_C(\text{kg/ha})]}{\text{Quantity of N applied (kg N/ha)}} \quad (1)$$

where,

F represents fertiliser treatment

C represents the control

Part of the air-dried grain samples was ground using an analytical mill to analyse for crude protein, crude fibre, carbohydrates using standard laboratory methods, while the energy and ash content were calculated (AOAC, 1990).

Economic analysis

Gross margin (Equation 2), benefit-cost ratio (BCR) (Equation 3), and return on investment (Equation 4) were computed to determine the economic performance of BSF frass fertiliser (Onsongo *et al.*, 2018). Price data for fertilisers and maize seed were obtained from Africa fertiliser (Africa Fertilizer, 2019) and Kenya farmers' association, respectively. Labour expenses (land preparation, planting, weeding and harvesting) were calculated by recording the time taken to perform each activity and valuing labour at the rate of 1.25 USD per hour (Kenyan Government, 2019). The price of maize grain was obtained from human data exchange (<https://data.humdata.org>). Since stover is used as an animal feed in Kenya, it was valued at 22.1 USD per tonne (Mucheru-Muna *et al.*, 2014).

$$\text{Gross margin (\%)} = \frac{\text{Net income}}{\text{Gross income}} \times 100 \quad (2)$$

$$\text{Benefit to cost ratio} = \frac{\text{Net income}}{\text{Total variable costs}} \quad (3)$$

$$\text{Return on investment} = \frac{\text{Net income}}{\text{Total variable costs}} \times 100 \quad (4)$$

where,

$$\text{Net income} = \text{Gross income} - \text{Total variable costs}$$

Total variable costs include cost of fertilisers and maize seeds, and labour expenses from land preparation to harvesting.

Data analysis

Data were checked for normality using the Shapiro-Wilk test. Data on plant height, number of leaves, stem diameter, chlorophyll concentration was analysed using a linear mixed-effect model with 'lmer' function from the package 'lme4' in R statistical software with fertiliser treatment and sampling time as fixed effects, and replication as random effect. Analysis of variances was performed on maize grain and stover yields and agronomic nitrogen use efficiency. Computation of least squares means was done using 'lsmeans' package. Significant means were compared

using the Student Newman Keuls Test at $P \leq 0.05$. All the statistical analyses were conducted using R software version 3.6.0 (R Core Team, 2019).

3. Results

Maize plant height, leaf growth, and stem diameter

The different fertiliser treatments caused significant ($P < 0.001$) differences in plant height during experiments. At four weeks, the plant height ranged between 23 and 54 cm, from where it increased significantly up to 12 weeks. Thereafter, the plant height increased slightly to reach peak values (66–197 cm) at 16 weeks. Maize grown using fertiliser treatments was significantly taller than maize grown using the control treatment throughout the experiments. Pots treated with BSFFF produced significantly taller maize plants than pots amended using Evergrow and BSG compost. Likewise, maize grown using BSFFF/NPK was significantly taller than that grown in soil amended with NPK and BSGNPK treatments at 12 and 16 weeks after planting. Pots amended with BSFFF/NPK produced the tallest maize plants (197 cm), 11, 17, 48, 88% taller than those grown using NPK, BSG/NPK, BSG and Evergrow fertilisers, respectively (Table 3).

There were significant differences ($P < 0.001$) in the number of leaves of maize plants treated with different fertiliser treatments (Table 3). Pots treated with fertiliser treatments produced maize with a higher number of leaves than those grown using the control treatment. Maize grown using BSFFF/NPK produced a significantly higher number of leaves than maize grown using other fertiliser treatments at 8, 12, and 16 weeks after planting. Likewise, pots treated with BSG/NPK produced maize plants with a significantly higher number of leaves than those amended with BSG compost and Evergrow at 8, 12, and 16 weeks after planting (Table 3).

The maize stem diameter was also observed to vary significantly ($P < 0.001$) due to different fertiliser amendments (Table 3). The maize stem diameter followed an increasing trend throughout the study, with minimal changes observed at 16 weeks after planting. All fertiliser treated pots produced maize plants with significantly bigger stem diameters than the control treatment. At four and eight weeks, maize grown in pots amended with a BSFFF/NPK had significantly bigger stem diameter than that produced using the control, BSG and Evergrow treatments. Similarly, use of BSFFF/NPK produced maize with significantly bigger stem diameters than at 10 and 12 weeks after planting. The biggest stem diameter (29.5 mm) was recorded at 16 weeks after planting from maize grown using BSFFF/NPK, and this was 11, 55, 27, and 18% higher than those achieved using NPK, Evergrow, BSG, and BSG/NPK, respectively (Table 3).

Table 3. Effect of various fertiliser types on maize plant height, leaf growth, and stem diameter.¹

Parameter	Treatment	Week 4	Week 8	Week 12	Week 16
Height (cm)	BSFFF	54.1±2.95a	109.4±3.85a	170.3±4.89b	177.3±5.51b
	BSG	41.5±1.98b	83.0±2.77b	130.7±7.31c	133.4±7.75c
	NPK	49.6±4.20ab	103.1±7.66a	171.9±7.22b	178.5±6.26b
	Evergrow	41.7±0.64b	68.3±1.74c	98.8±4.84d	104.7±4.73d
	BSFFF/NPK	49.1±1.32ab	108.3±4.06a	192.6±4.98a	197.3±5.13a
	BSG/NPK	49.5±2.04ab	102.7±4.17a	164.6±5.40b	169.3±6.06b
	Control	23.2±1.21c	44.7±1.63d	64.0±3.37e	65.7±3.32e
	<i>P</i> -value	<0.001	<0.001	<0.001	<0.001
Number of leaves	BSFFF	8.0±0.31a	10.5±0.24b	12.4±0.17b	13.9±0.14b
	BSG	6.7±0.48a	8.7±0.25c	10.6±0.30c	11.3±0.39c
	NPK	7.6±0.42a	10.8±0.32b	12.7±0.33b	13.7±0.40b
	Evergrow	7.4±0.24a	8.2±0.20c	10.1±0.31c	11.1±0.41c
	BSFFF/NPK	7.4±0.16a	11.8±0.13a	13.8±0.18a	14.8±0.09a
	BSG/NPK	7.5±0.22a	10.3±0.21b	12.2±0.23b	13.3±0.15b
	Control	5.7±0.36b	6.3±0.39d	7.9±0.13d	8.5±0.19d
	<i>P</i> -value	0.001	<0.001	<0.001	<0.001
Stem diameter (mm)	BSFFF	15.3±0.96a	24.8±0.37a	26.1±0.12b	27.6±0.20b
	BSG	10.5±0.52b	19.7±1.05b	22.3±0.92c	23.2±0.97d
	NPK	13.2±1.14a	23.1±1.53ab	25.9±0.36b	26.5±0.30bc
	Evergrow	10.5±0.60b	14.8±0.73c	18.4±0.78d	19.1±0.76e
	BSFFF/NPK	14.1±0.75a	25.6±1.30a	28.0±1.05a	29.5±0.90a
	BSG/NPK	12.9±0.57a	23.2±0.64ab	24.4±0.19b	25.0±0.32bc
	Control	4.9±0.21c	7.9±0.94d	9.2±0.32e	9.7±0.19f
	<i>P</i> -value	<0.001	<0.001	<0.001	<0.001

¹ BSFFF = black soldier fly frass fertiliser; BSFFF/NPK = black soldier fly frass fertiliser and NPK; BSG = brewery spent grain compost; BSG/NPK = brewery spent grain compost and NPK; control = unamended soil; Evergrow = commercial organic fertiliser; NPK = mineral fertiliser. Within the same column, means (±standard error) followed by the same letter are not significantly different at $P \leq 0.05$.

Chlorophyll concentration

The maize leaf chlorophyll concentration was significantly ($P < 0.001$) influenced by the different fertiliser treatments (Figure 1). The leaf chlorophyll concentrations of maize grown using fertiliser treatments significantly increased to peak levels (32–49 SPAD values) at eight weeks after planting and decreased afterward, except for Evergrow treatment, which reached peak values at 16 weeks after planting. Maize grown in pots treated with BSF NPK had significantly higher leaf chlorophyll concentrations than other treatments, except Evergrow at 16 weeks after planting (Figure 1).

All fertiliser treated pots produced maize with significantly higher leaf chlorophyll concentrations than the control treatment from the eighth week of experiments (Figure 1). The highest leaf chlorophyll concentration was achieved at eight weeks after planting from maize grown using BSFFF/NPK, and this was 22, 25, 26, 46, and 53% higher than those of maize grown using NPK, BSG/NPK, BSFFF, Evergrow, and BSG, respectively. Similarly, the leaf chlorophyll concentration of maize grown using BSFFF/NPK was

significantly higher than those of other treatments by 23–88% at 16 weeks after planting, except where Evergrow fertiliser was applied (Table 1).

Maize grain and stover yields

The different fertiliser amendments caused significant ($P < 0.001$) differences in maize grain yield (Figure 2). Fertiliser application increased maize grain yield by 46–111% higher than the control treatment. The highest grain yield (7.98 t/ha) was produced from maize grown in pots treated with BSFFF/NPK, and this was 23–68% higher than the grain yields achieved using other fertiliser treatments. Maize grain yields from pots treated with BSFFF, NPK, and BSG/NPK were significantly higher than those produced using Evergrow and sole BSG compost. Furthermore, the grain yield from maize grown in pots treated with BSFFF was 73 and 153% higher than those produced using BSG and Evergrow fertiliser, respectively.

The maize stover yield also varied significantly ($P < 0.001$) due to different fertiliser treatments. Maize grown using

Figure 1. Effect of various fertiliser types on maize leaf chlorophyll concentration. BSFFF = black soldier fly frass fertiliser; BSFFF/NPK = black soldier fly frass fertiliser and NPK; BSG = brewery spent grain compost; BSG/NPK = brewery spent grain compost and NPK; control = unamended soil; Evergrow = commercial organic fertiliser; NPK = mineral fertiliser.

Figure 2. Effect of various fertiliser types on maize grain and stover yields. BSFFF = black soldier fly frass fertiliser; BSFFF/NPK = black soldier fly frass fertiliser and NPK; BSG = brewery spent grain compost; BSG/NPK = brewery spent grain compost and NPK; control = unamended soil; Evergrow = commercial organic fertiliser; NPK = mineral fertiliser. Means followed by the same letters are not significantly different at $P \leq 0.05$.

BSFFF, NPK, and BSG/NPK produced significantly higher stover yields than the maize produced using BSG and Evergrow. All fertiliser treated pots produced significantly higher maize stover yield than the control treatment (Figure 2).

Agronomic nitrogen use efficiency and economic returns

The different fertiliser treatments caused significant ($P<0.001$) variations in the maize AE_N (Figure 3). The AE_N of maize grown using BSFFF/NPK was significantly higher than those of maize grown using the BSG and Evergrow, by 2.1 and 3.1 times, respectively. Likewise, the AE_N of maize grown using BSFFF, NPK, and BSG/NPK were significantly higher than that of maize harvested from plots amended with Evergrow by 153, 149, and 127%, respectively. Maize grown using BSFFF/NPK achieved the highest AE_N (79.8 kg/kg N), which was 23, 25, and 38% higher than those achieved using BSFFF, NPK, and BSG/NPK, respectively. On the other hand, the lowest maize AE_N (25.6 kg/kg N) was recorded in maize grown using Evergrow fertiliser (Figure 3).

Figure 3. Agronomic nitrogen use efficiency of maize grown using various fertiliser types. BSFFF = black soldier fly frass fertiliser; BSFFF/NPK = black soldier fly frass fertiliser and NPK; BSG = brewery spent grain compost; BSG/NPK = brewery spent grain compost and NPK; Evergrow = commercial organic fertiliser; NPK = mineral fertiliser. Means followed by the same letters are not significantly different at $P\leq 0.05$.

The economic returns from maize produced using different fertiliser treatments are presented in Table 4. Maize grown using BSFFF/NPK fertilisers generated the highest net income, which was 2, 163, and 173% higher than those achieved using NPK, BSG/NPK, and BSFFF, respectively. The highest gross margin, BCR, and return on investment were achieved from maize grown using NPK, followed by maize harvested from pots amended with BSFFF/NPK.

However, maize grown using Evergrow, BSG, and the control treatments yielded negative values of net income, gross margin, benefit-cost ratio and return on investment (Table 4)

Maize nutritional quality

There were significant differences ($P<0.001$) in the crude protein levels of maize grown using different fertiliser treatments (Table 5). All fertiliser treatments produced maize with significantly higher (20-75%) crude protein content than the control. Grain harvested from maize grown using BSFFF/NPK fertilisers achieved the highest crude protein content, which was significantly higher than those of maize grown using other treatments. The crude protein content of maize grown using BSFFF was significantly higher than those of maize grown using BSG, Evergrow, and BSG/NPK by 31, 29, and 10%, respectively (Table 5).

The crude fat content of maize also varied significantly ($P<0.001$) due to different fertiliser amendments (Table 5). The crude fat contents of maize grown using BSG and Evergrow and control were significantly higher than those of other fertiliser treatments, except where NPK was applied. Maize grown in pots amended with BSG achieved the highest crude fat content, while the pots treated with BSFFF produced maize with the lowest crude fat content. There were significant ($P<0.001$) differences in the crude fibre content of maize grown using different fertiliser amendments (Table 5).

All fertiliser treatments produced maize with significantly higher crude fat content than control. Maize grown using BSFFF/NPK, Evergrow, and BSG/NPK achieved significantly higher crude fat levels than the fertiliser treatments, except NPK (Table 5). The control treatment produced maize grains with significantly higher ash content than all fertiliser treatments (Table 5). Maize grown using BSFFF and BSG/NPK had the highest ash contents among the fertiliser treatments. In contrast, pots amended with Evergrow and BSFFF/NPK produced maize with the least ash contents (Table 5).

The carbohydrate content and energy levels of maize grown using different fertilisers also varied significantly ($P<0.001$). The control treatment produced maize grains with significantly higher carbohydrates content than other

Table 4. Net income and gross margin generated from maize produced using various fertiliser types.¹

Fertiliser treatment	Net income (US dollar)	Gross margin (%)	Benefit-cost ratio	Return on investment (%)
BSFFF	789.6	26.5	0.38	38.4
BSG	-1,150.9	-71.9	-0.41	-40.6
NPK	2,116.8	73.3	2.91	290.5
Evergrow	-5,180.7	-467.1	-0.81	-81.3
BSFFF/NPK	2,156.8	59.9	1.55	154.9
BSG/NPK	818.7	27.4	0.46	45.9
Control	-7.6	-2.3	-0.02	-2.0

¹ BSFFF = black soldier fly frass fertiliser; BSFFF/NPK = black soldier fly frass fertiliser and NPK; BSG = brewery spent grain compost; BSG/NPK = brewery spent grain compost and NPK; control = unamended soil; Evergrow = commercial organic fertiliser; NPK = mineral fertiliser.

Table 5. Nutritional value of grain from maize grown using various fertiliser types.¹

Fertiliser treatment	Crude protein (%)	Crude fat (%)	Crude fibre (%)	Ash content (%)	Carbohydrates (%)	Energy (kcal/100 g)
BSFFF	8.0±0.29b	4.2±0.31c	2.7±0.13b	1.3±0.07b	74.2±0.85bc	375.7±2.01b
BSG	6.1±0.32c	6.8±0.24a	2.5±0.13b	1.2±0.07b	73.6±0.59bc	390.2±1.95a
NPK	7.6±0.2b	5.2±0.1bc	3.0±0.11a	1.1±0.05b	73.2±0.39bc	379.1±1.47b
Evergrow	6.2±0.41c	5.7±0.5ab	2.7±0.06ab	1.0±0.04b	75.3±0.77ab	387.2±2.61a
BSFFF/NPK	8.9±0.28a	4.2±0.21c	3.3±0.16a	1.0±0.04b	72.4±0.17c	372.1±2.03b
BSG/NPK	7.3±0.24b	4.5±0.35c	3.2±0.12a	1.3±0.08b	73.4±0.82bc	372.4±2.4b
Control	5.1±0.21d	6.3±0.32a	2.1±0.1c	1.5±0.05a	76.7±0.23a	393.7±2.31a

¹ BSFFF = black soldier fly frass fertiliser; BSFFF/NPK = black soldier fly frass fertiliser and NPK; BSG = brewery spent grain compost; BSG/NPK = brewery spent grain compost and NPK; control = unamended soil; Evergrow = commercial organic fertiliser; NPK = mineral fertiliser. Within the same column, means (±standard error) followed by the same letter are not significantly different at $P \leq 0.05$.

treatments, except Evergrow. On the other hand, maize harvested from the control pots, and pots amended with Evergrow and BSG had significantly higher energy levels than those of maize grown using other treatments (Table 5).

4. Discussion

Effect of various fertiliser types on maize growth and yield

The BSF larval-based waste management technologies are crucial in converting the huge quantities of nutrients contained in waste streams into nutrient-rich larval biomass for incorporation as alternative protein additive in animal feeds, and high quality organic frass fertiliser for crop production. The integration of frass fertiliser into cropping practices would help to return nutrients back into the soil and increase farm productivity through reduced expenses on animal feed and fertiliser inputs. The non-significant differences in maize yield and AE_N observed between BSFFF and NPK treatments indicate that the BSF frass fertiliser can perform as good as most commercial mineral fertilisers available in the market as previously reported by Beesigamukama *et al.* (2020c). This study's

findings are crucial in changing attitudes towards organic fertiliser use, with the advantage of less bulkiness and high nutrient concentrations associated with high-quality organic fertilisers such as the BSF frass fertiliser. However, a tendency in higher maize grain yield and agronomic nitrogen use efficiency achieved using a combination of NPK and BSF frass fertilisers compared to sole NPK highlight the key role of organic fertilisers in integrated soil fertility management, especially improving nutrient availability and soil moisture retention (Geng *et al.*, 2019; Nsoanya and Nweke, 2015; Quansah, 2010; Vanlauwe *et al.*, 2015).

The higher maize growth and grain yields associated with all fertiliser treatments compared to the control (unamended soil) treatment are in line with previous studies (Gachimbi *et al.*, 2005; Muchena *et al.*, 2005; Tully *et al.*, 2015), which have highlighted low soil fertility as one of the major factors limiting crop production in most SSA regions. Table 1 shows that the experimental soil was deficient in major nutrients required for maize production. Therefore, the use of quality fertiliser such as the BSF frass fertiliser could be an entry point for improving maize production, as demonstrated by

the higher maize yield achieved (Figure 2). Our findings align with Beesigamukama *et al.* (2020c) and Quilliam *et al.* (2020), who reported higher growth, yield, and agronomic nitrogen use efficiency of maize grown in plots treated with BSF frass fertiliser due to the high N mineralisation and nutrient release rates (Adin Yéton *et al.*, 2019).

The higher nutrient concentrations and lower C/N ratio associated with BSF composted organic fertiliser (Table 2) highlight the high efficiency of BSF larvae in nutrient recycling, which has been previously reported (Beesigamukama *et al.*, 2021; Lalander *et al.*, 2015). Organic fertilisers with lower C/N ratios, such as the BSF frass fertiliser are associated with faster nutrient release for crop production, and vice versa (Palomba, 2016). The higher maize chlorophyll concentration observed using BSFFF and BSFFF/NPK indicates the higher photosynthetic activity and nitrogen accumulation arising from the synergistic effect of combining fertilisers than using sole organic or sole mineral fertilisers (Figure 1). Nitrogen is essential in photosynthesis, cell division, protein formation, and vegetative growth (Kogbe and Adediran, 2003), which could have contributed to the better maize growth, yield, and agronomic nitrogen use efficiency of maize grown using the BSF frass fertiliser.

The observations described above are in line with the report by Beesigamukama *et al.* (2020b,c) and Kagata and Ohgushi (2012), who demonstrated that frass fertiliser is capable of improving soil nutrient availability, plant growth, and yield. Although not demonstrated in this study, the use of insect frass fertiliser has additional benefits for crop production, such as improved drought and salt tolerance, and disease suppression (Choi and Hassanzadeh, 2019; Houben *et al.*, 2020). Furthermore, deeper plant root growth and spread due to plant growth-promoting organisms and growth hormones, such as auxin and gibberellins, have been reported while using insect frass as a biofertiliser (Poveda *et al.*, 2019). Such behaviour of root growth could have been crucial in the nutrient acquisition by maize grown using BSF frass fertiliser, and consequently, the higher grain yield. The higher values of maize growth and yield achieved in treatments that received NPK alone compared to sole Evergrow, and BSG compost could be attributed to the higher nutrient availability associated with mineral fertilisers (Adebayo, 2017; Ojo *et al.*, 2014).

Nutritional quality and economic returns from maize grown using various fertiliser types

The higher crude protein contents of maize grown using BSF frass fertiliser compared to the commercial fertilisers could be attributed to higher nutrient uptake, as reported previously (Beesigamukama *et al.*, 2020b,c). This is because nitrogen is an integral part of amino acids. On the other hand, insect frass fertilisers are associated

with better mineral nutrition, hence the higher crude protein in maize grown in pots amended with BSF frass fertiliser (Houben *et al.*, 2020). The higher grain yield and nutritional quality of maize grown using BSF frass fertiliser indicate the role this product could play in improving food and nutrition security among the vulnerable segments particularly women and children in the rapidly growing populations in most developing countries. Therefore, the development of inclusive business models involving BSFFF as additional value-added product from insect farming would significantly contribute to solving socio-economic and environmental problems in developing countries, aligning with the United Nations' Sustainable Development Goals 1, 2, 5, 6, 8, 9, 11, 12 and 15. With low initial capital investments, smallholder insect farmers have good opportunities to increase productivity, improve their livelihood and contribute to food security and a circular economy.

The negative values of net income recorded in maize grown using sole BSG compost and sole Evergrow indicate the poor quality yet expensive organic fertilisers used in most cropping systems of low- and middle-income countries. This could greatly decrease farm productivity. On the other hand, the higher net income achieved using BSF frass fertiliser compared to the conventional and commercial organic fertilisers indicates the high potential of insect frass fertiliser for increasing crop productivity. Furthermore, the increase in net income attained using a combination of BSF frass and NPK fertilisers compared to sole NPK highlights the role of frass fertiliser in increasing the profitability of maize production while reducing the high fertiliser costs associated with mineral fertiliser (Adamtey *et al.*, 2016; Gram *et al.*, 2020; Vanlauwe *et al.*, 2015). Consequently, the adoption of high-quality and affordable organic fertilisers such as the BSF frass fertiliser could sustainably increase farm productivity (Ndambi *et al.*, 2019; Rufino *et al.*, 2007) and lift farmers out of poverty. The frass fertiliser can also be sold directly, thus increasing the household income of insect farmers. Therefore, BSF farming has potential to create jobs for the women and youths involved in the insect production chain, while conserving the environment by using the BSF larvae as biowaste converters (Chia *et al.*, 2019).

5. Conclusion

The current study has revealed for the first time that the high fertiliser value of composted black soldier fly frass and its integration with mineral NPK fertiliser could be a solution for improved soil health and sustainable production of maize. The higher economic returns and nutritional quality of maize achieved using the BSF frass fertiliser indicate great potential for increasing household income, food, and nutrition security of smallholder farmers in low- and middle-income countries. Therefore, the BSF frass

fertiliser should be considered an affordable and sustainable source of nutrients for improving soil fertility and crop yield. This study paves a pathway to cleaner production technologies by using the BSF larvae to recycle nutrients in organic waste into high-value insect-protein for livestock feeding and nutrient-rich organic fertiliser for improved soil health and crop productivity. Nevertheless, on-farm research is required to validate the current findings for large scale frass fertiliser application in Africa and beyond.

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Conflict of interest

The authors declare no conflict of interest.

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