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Economic and ecological values of frass fertiliser from black soldier fly agro-industrial waste processing

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RESEARCH ARTICLE

Abstract

The sustainable utilisation of black soldier fly (BSF) for recycling organic waste into high-quality protein feed and organic fertiliser with a low environmental footprint is gaining momentum worldwide. Although BSF farming is becoming a rapidly growing agribusiness, studies on the BSF farming's economic aspects are limited. This study analysed the economic benefits of farming BSF for animal feeds and composted frass, called frass fertiliser (FF) production using experimental data. The BSF larvae were fed on brewery spent grain amended with sawdust, biochar, and gypsum to determine the cost-effective feed and other by-products production. The agronomic performance of FF on the maize crop was assessed using field experiments. Our results demonstrated that sourcing and preparing the waste substrate for rearing the BSF larvae accounts for 81-90% of the total BSF production cost. The utilisation of FF as an additional value-added product would increase farmer's net income by 5-15 folds compared to BSF farming alone. Feedstock amended with 20% biochar increased net income by 10-64% for BSF larvae and FF production than other feedstocks. Production of one megagram (Mg) of dried BSF larvae (USD 900) would generate 10-34 Mg of FF worth USD 3,000-10,200. Maize grown on plots treated with FF yielded 29-44% higher net income than maize harvested from plots amended with commercial organic fertiliser. Furthermore, smallholder insect farmers' direct use of FF for maize production would generate 30-232% higher net income than farmers purchasing similar FF. Our results demonstrate for the first time the role of insect farming in circular economy and justify the opportunities for future investments that would lead to enhanced sustainability for agricultural and food systems, especially for smallholder farmers in low- and middle-income countries.

Keywords: black soldier fly farming, frass fertiliser, maize production, profitability, circular economy

1. Introduction

Poor soil health and feed scarcity are among major challenges affecting the food and nutrition security of sub-Saharan Africa (SSA) (Alltech, 2016; Ssepuuya *et al.*, 2017; Tully *et al.*, 2015). Most soils (40%) in SSA are nutrient deficient (Cobo *et al.*, 2010; Tully *et al.*, 2015), and yet, very little (≤10 kg/ha/year) or no mineral fertiliser is used due to high prices and limited access (FAO, 2017; Stewart *et al.*, 2020). Even in the few farms where mineral fertilisers are used, low agronomic use efficiencies and crop yields have been reported (Kihara *et al.*, 2016; Liverpool-Tasie *et al.*, 2017), mostly attributed to low soil organic matter levels, secondary and micronutrient deficiencies, and high acidity (Vanlauwe *et al.*, 2015; Wortmann *et al.*, 2019). Previous research efforts on soil fertility management in SSA (Stewart *et al.*, 2020; Tittonell *et al.*, 2008; Vanlauwe *et al.*, 2014, 2015) have recommended the combined

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application of mineral and organic fertilisers to improve and sustain soil health and crop yields. However, the use of organic fertilisers is greatly hindered by the limited source of organic matter since most organic resources have other competing uses, such as feeding livestock on the farm (Ndambi *et al.*, 2019; Rufino *et al.*, 2011). In addition to the low crop productivity, animal (fish, poultry, and piggery) production in SSA is also constrained by feed scarcity since the conventional protein sources such as fish and soy meal have become scarce and more expensive (Ssepuuya *et al.*, 2017).

Insects have been recommended as as alternative sources of animal feeds and efficient recyclers of organic waste into quality organic fertiliser (Beesigamukama *et al.*, 2021; Makkar *et al.,* 2014; Van Huis, 2013). Insects as feed and food are increasingly gaining momentum due to the high cost of conventional feed sources, high demand for animal protein, and concerns related to climate change impact caused by conventional feed sources and animal products (Dobermann *et al.*, 2017; Mertenat *et al.*, 2019; Van Huis and Oonincx, 2017). Recent estimates have put the global feed market demand at 464, 254, 35, and 23 million megagrams (Mg) for poultry, pigs, cultured fish, and pets, respectively (Alltech, 2016). Therefore, the use of insect-based feeds is expected to contribute immensely to the global feed supply while mitigating adverse environmental effects (Dobermann *et al.*, 2017; Makkar *et al.*, 2014).

The black soldier fly (BSF) (*Hermetia illucens* L.) is a widely distributed insect in the tropics with high nutritional value and waste conversion efficiency (Dobermann *et al.*, 2017). The dry BSF larvae contain about 42-49% crude proteins, 38% lipids, 20% crude fiber, 20% ash, and vitamins (Makkar *et al.*, 2014), which have been shown to improve poultry (Kierończyk *et al.*, 2020; Schiavone *et al.*, 2017; Sypniewski *et al.*, 2020), pig, and fish (Kroeckel *et al.*, 2012; Magalhães *et al.*, 2017) production. In Kenya, the potential macroeconomic impact of adopting BSF larval meals in the poultry sector has been estimated at 16-687 million USD per year (Abro *et al.*, 2020), not forgetting other benefits such as job creation along the value chain and the value of environmental sanitisation.

Recent studies show BSF's technical and potential economic feasibility (Abro *et al.*, 2020; Chia *et al.*, 2019), however, insect production still faces many hurdles, including selecting an effective rearing substrate (Dobermann *et al.*, 2017; Makkar *et al.*, 2014; Van Huis, 2013). The required quantities of organic wastes to rear BSF may not be readily available on the farm for mass production. This implies that insect farmers would incur costs to either purchase or transport rearing substrates or both. Our preliminary assessments have shown that, the rearing substrate alone accounts for the highest share of overhead costs during BSF rearing. Such costs may not be covered only by revenues generated from sales of insect larvae. The second source of revenue from sales or use of the utilised rearing substrates may also be required.

Combining BSF protein with organic fertiliser production could make BSF rearing more profitable (Figure 1). Moreover, recent studies have reported increased growth and yield of crops grown using BSF frass fertiliser (Beesigamukama *et al.*, 2020a; Bortolini *et al.*, 2020; Choi and Hassanzadeh, 2019; Quilliam *et al.*, 2020). The BSF frass fertiliser is a by-product that is gaining popularity due to its high nutrient content and potential for use as organic fertiliser (Anyega *et al.*, 2021; Bortolini *et al.*, 2020; Gärttling *et al.*, 2020; Lalander *et al.*, 2015; Oonincx *et al.*, 2015; Setti *et al.*, 2019). Generating frass fertiliser from BSF farming would create a valuable product for farmers already producing BSF larvae for animal feeding purposes.

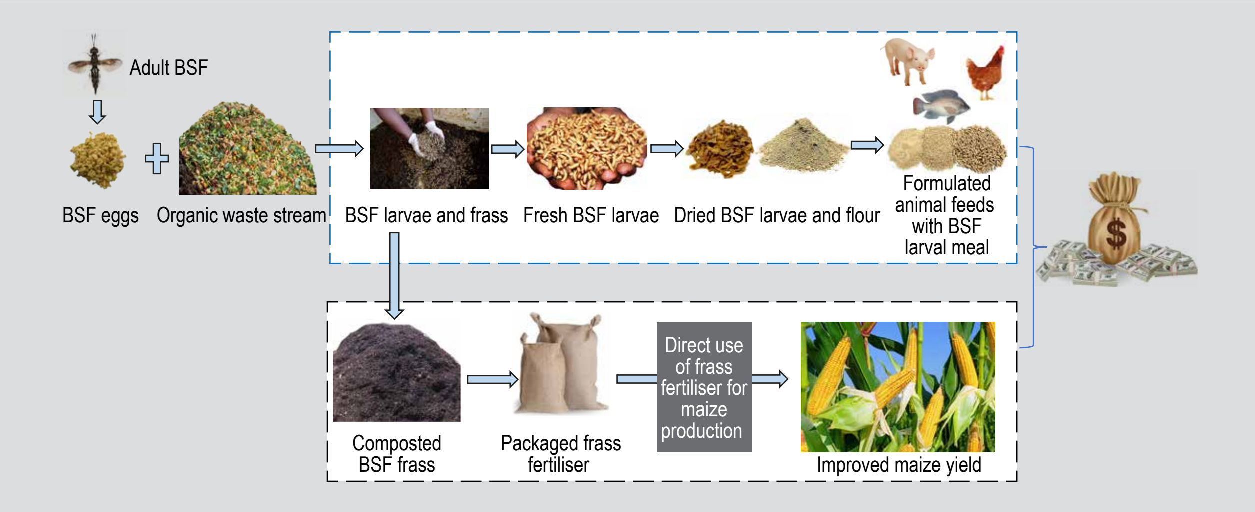

Figure 1. Schematic diagram of black soldier fly (BSF) circular economy production system.

Although some studies show the nutritional profile of BSF larvae and the technical feasibility of BSF farming, there is still limited research that shows the economic benefits of frass fertiliser. Abro *et al.* (2020), using a replacement cost approach, estimated the macroeconomic gains of BSF frass at 9-85 million USD in Kenya. However, their estimate did not consider the cost of producing frass fertiliser and the direct economic benefits that can be achieved while using frass fertiliser for crop production. This paper addresses this gap by estimating the economic value of producing frass fertiliser as a new value-added product of BSF farming for maize production. We further assess the optimum frass fertiliser required for maximum maize production.

2. Materials and methods

Economic value of frass fertiliser as a by-product of black soldier fly farming

We used gross margins, benefit-cost ratio, and return on investment to assess frass fertilisers' technical and economic efficiency. These were computed as follow (Chia *et al.*, 2019):

$$Gross\ margin\ (\%) = \frac{Net\ income}{Gross\ income} \times 100 \quad (1)$$

$$Benefit-cost\ ratio\ = \frac{Net\ income}{Total\ variable\ costs} \quad (2)$$

$$Return\ on\ investment\ (\%) = \frac{Net\ income}{Total\ variable\ costs} \times 100 \quad (3)$$

where *Net income = Gross income – Total variable costs.*

The economic analysis was computed under two options: (1) BSF farming solely for larvae production; and (2) BSF farming for larvae and frass fertiliser production. Under the first option, the BSF production process ended at the 5th instar larval stage, when the larvae are usually harvested and processed for animal feeding purpose. The variable costs of insect production included rearing substrates transport, water, electricity, and labor for egg collection, feeding, and harvesting and drying the BSF larvae. Labor costs were calculated using a wage rate of 1.25 USD per hour (Kenya Government, 2019).

Under the second option, after larvae harvesting, frass was collected and composted to convert it into an organic fertiliser referred to as frass fertiliser, following the procedures described in Beesigamukama *et al.* (2020b). The additional costs incurred, such as transporting frass to the composting site and managing the frass to convert it into organic fertiliser, were added to the fertiliser production costs. The quantity of dry frass fertiliser and dry BSF larvae was obtained from each waste combination to measure the gross income.

The BSF larvae were reared in metallic trays using brewery spent grain (BSG) feedstock described by Shumo *et al.* (2019). BSG was chosen as the primary rearing substrate due to its high suitability for BSF larval performance (Chia *et al.*, 2018; Shumo *et al.*, 2019) and availability in large quantities. The BSG (one Mg dry weight) was amended with different quantities of sawdust (0, 9, 20, 32, and 44%), biochar (0, 5, 10, 15, and 20%), and gypsum (0, 5, 10, and 15%) to develop a substrate formulation that could conserve enough nutrients for cost-effective production of high BSF larval biomass and frass fertiliser (Beesigamukama *et al.*, 2020c, 2021; Huang *et al.*, 2004; Li *et al.*, 2018). The costs of substrate amendments (sawdust, biochar, and gypsum) were included as a part of production costs under the second option. After 14 days of rearing (5th instar stage), the BSF larvae were harvested, and the quantity of dry larvae obtained per treatment was recorded.

The performance of BSF larvae on BSG was comparable with those of other wastes such as chicken manure and kitchen waste (Shumo *et al.*, 2019) that can be readily available both on- and off-farm. We, therefore, considered two scenarios of rearing substrate in establishing the technical and economic benefits of frass fertiliser: (1) BSF farming when the main rearing substrate is purchased and transported to the farm; and (2) BSF farming when the main rearing substrate is available on the farm, i.e. no substrate acquisition costs (purchase or transport) incurred.

Impact of black soldier fly frass fertiliser on maize production

We conducted on-station field experiments for two seasons (April – September 2019 and October 2019 – March 2020) to determine the economic return to using organic fertiliser for maize production. We used gross margins, benefit-cost ratio, and return on investment as described in Equations 1 to 3. We compared the economic return to organic fertiliser from insect farming with mineral fertiliser (urea) and commercial organic fertiliser.

Price data for fertilisers and maize seed (variety H513) were obtained from Africa fertiliser and Kenya farmers' association (Africa Fertilizer, 2019). We estimated labor expenses (land preparation, planting, weeding, fertiliser application, and harvesting) by recording the time taken to perform each activity and valuing labor at the rate of 1.25 USD per hour (Kenya Government, 2019). Maize grain and stover yields were considered in the economic impact analysis of organic fertiliser for maize production. The price of maize grain was obtained from human data exchange (Humanitarian Data Exchange, 2020). Since stover is used as an animal feed in Kenya, it was considered an additional output and valued at 22.1 USD per Mg (Mucheru-Muna *et al.*, 2014).

The field tests consisted of the BSF frass fertiliser, commercial organic fertiliser (SAFI), and mineral nitrogen (N) fertiliser (46% N urea) each applied at three rates equivalent to 30, 60, and 100 kg N/ha. These experiments aimed to determine the optimum fertiliser application rates for maize production. The experiments were conducted on fields of 4×4 m in a randomised complete block design with three replicates per treatment. They were managed according to the recommended agronomic procedures up to maturity (Beesigamukama *et al.*, 2020a). Grain yield data were collected at the harvesting stage from each plot after all the ears had dried. Plants in the harvested area were cut at ground level, and their ears threshed to determine grain and residues' weights using a weighing scale. Grain and stover samples were taken to the laboratory and air-dried to 12.5% moisture content to determine grain and residues yields per plot and calculated on a hectare basis (kg/ha).

Economically optimum frass fertiliser rates for maize production

The maize grain yields were regressed as a function of fertiliser rates, and the response curve was drawn for each fertiliser treatment. The use of a quadratic function to determine optimum fertiliser rates is common in literature (Naher *et al.*, 2011).

$$Y = a + bN + cN^2 \tag{4}$$

Equation 4 used to determine the optimum nitrogen (N) fertiliser rate as:

$$N = \frac{E_n - b}{2c}$$

where,
Y is maize grain yield in kg per hectare
N is the rate of nitrogen fertiliser (kg/ha)
a, b, and c are parameters to be estimated
E_n represents the ratio of fertiliser price (P_f) to maize price (P_y), $E_n = P_f / P_y$
P_f represents the price of fertiliser (urea, frass fertiliser, and SAFI organic) per kg
P_y represents the price of maize per kg

3. Results and discussion

Economic returns of frass fertiliser to black soldier fly farming

The yields of BSF larva and frass fertiliser and economic return from two BSF farming scenarios are presented in Tables 1 and 2. The rearing substrate cost accounted for the most expenses of BSF farming (81-90%) (Table 1 and 2), while costs incurred on substrates amended by sawdust were minimal. This study has demonstrated that a farmer who incurs costs of purchasing and transporting the rearing substrates for larval production only would be operating at a loss indicated by the negative net income values (Table 1 and 2). This is further confirmed by the negative values of return on investment, benefit-cost ratio and gross margin (Figure 2).

The combination of BSF larvae and frass fertiliser considerably increases the income from insect framing. This study has established that for every kg of BSF larvae produced, 10-17, 10-19, 19-34, and 12-15 kg of frass fertiliser are generated using the unamended substrate, substrates amended with sawdust (Table 1), gypsum, and biochar (Table 2), respectively. However, even with organic fertiliser production, BSF farming is still nonprofitable if the BSF farmer incurs costs on the rearing substrate (Table 1 and 2). Contrarily, amending the substrate with 20% sawdust and producing organic fertiliser from the frass can generate positive profit even if the BSF farmer incurs costs on the rearing substrate. Therefore, any strategy for improving the profitability of BSF farming should consider the rearing substrate's availability at a low or affordable cost.

The net income was positive when the rearing substrate's cost was excluded, that is, when the substrate is available on the farm (Table 1 and 2). However, this was only achieved in production systems where both larvae and frass fertiliser production are considered, indicating that frass fertiliser is crucial for improving BSF farming's cost-effectiveness. This study estimated that the production of 1 Mg of dried BSF larvae (USD 900) would generate 10-34 Mg of frass fertiliser worth USD 3,000-10,200. Results indicate that net income increased by 11-15, 4.8-4.9, and 5-6 times for substrates amended with sawdust (Table 1), gypsum, and biochar (Table 2), respectively, compared to rearing BSF for larvae production alone. For example, amending the rearing substrate with 20% sawdust increased the net income from BSF larvae and frass fertiliser by 33% compared to the unamended substrate (Table 1). Simialrly, amending the rearing substrate with gypsum and biochar increased the net income from BSF larvae and frass fertiliser by 5-8 and 3-28%, respectively, compared to the unamended substrate (Table 2). The higher net income achieved from substrates amended with 15 and 20% biochar can be attributed to the positive impact of biochar on both larval and frass fertiliser yields. Biochar is a bulking agent, and its amendment improves nutrient and moisture retention and porosity of organic substrates, which are favorable for BSF larval growth and yield (Sanchez-Monedero *et al.*, 2018).

The high gross margin and return on investment (Figure 2) obtained using unamended substrate indicate that generating organic fertiliser as a second high valuable product from BSF farming has a high potential to benefit farm households which are liquidity constrained to purchase ingredients to amend substrates. However, since the net income generated using an amended substrate with either

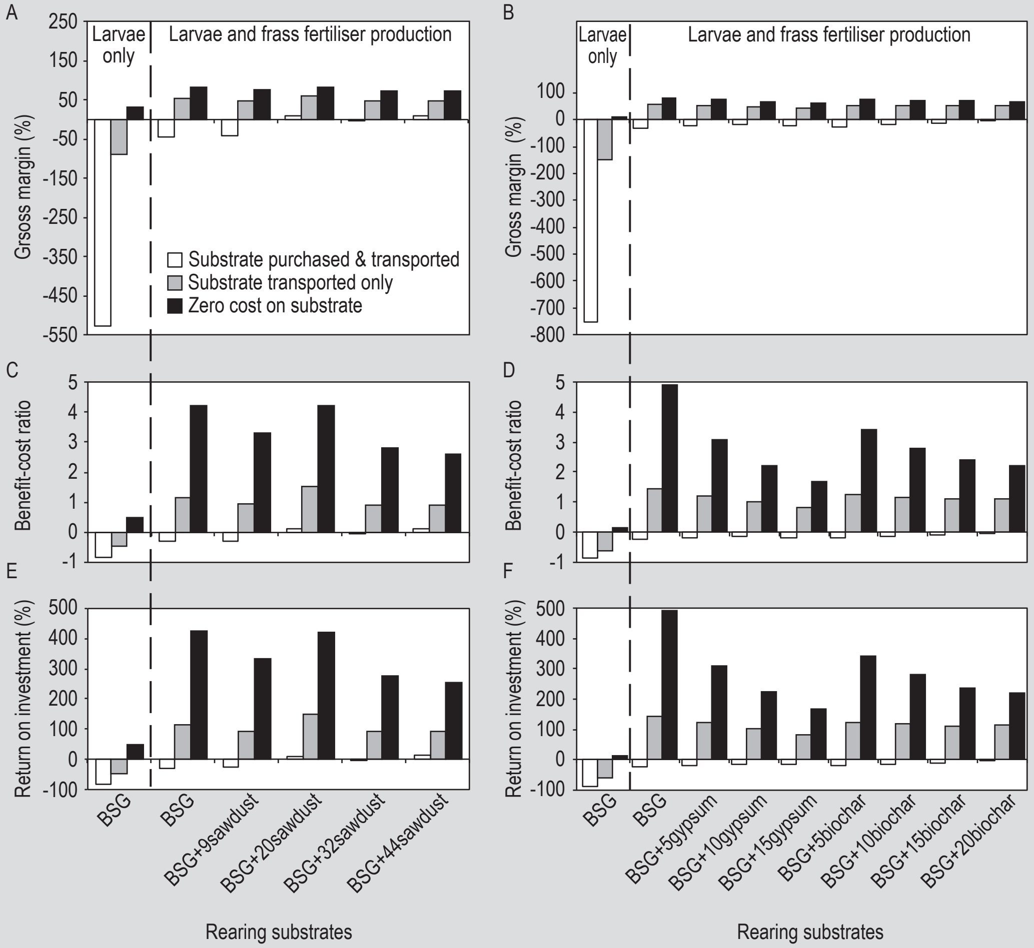

Figure 2. Gross margin (A and B), benefit-cost ratio (C and D), and return on investments (E and F) from two black soldier fly farming scenarios using rearing substrates amended with sawdust (A, B and C), biochar and gypsum (B, D and F). BSG = brewery spent grain.

Table 1. Economic returns from black soldier fly (BSF) production using sawdust amended rearing substrates.[1]

Rearing substrates	Cost of rearing substrate as % of production costs	Larval yield (kg)	Frass fertiliser yield (kg)	Income from BSF larvae (USD)	Income from BSF frass fertiliser (USD)	Gross income (USD)	Income from frass fertiliser as % of gross income (%)	Net income per Mg of rearing substrate (USD)	
								Substrate purchased & transported	Zero cost on substrate
BSF farming for larvae production only									
BSG	89.3	45.3	na	40.7	na	40.7	na	-214.1	13.4
BSF farming for larvae and frass fertiliser production									
BSG	86.7	45.3	472	40.7	141.7	182.5	77.6	-79.9	147.6
BSG+9sawdust	85.7	43.2	451	38.9	135.4	174.3	77.6	-68.8	134.0
BSG+20sawdust	84.3	37.4	696	33.6	208.8	242.4	86.1	22.4	195.9
BSG+32sawdust	82.6	32.1	555	28.9	166.5	195.4	85.2	-50.7	143.3
BSG+44sawdsut	81.0	34.2	580	30.9	174.0	204.8	84.8	21.1	147.2

[1] Costs of production: BSG = 0.0522 USD/kg, sawdust = 0.02 USD/kg, labour = 1.25 USD/hour. Sources of revenue: BSF larvae = 0.9 USD/kg, frass fertiliser = 0.3 USD/kg.

[2] BSG = brewery spent grains, 9sawdsut, 20sawdust, 32sawdust and 44sawdust = amendment of brewery spent grain with sawdust at inclusion levels of 9, 20, 32 and 44% (weight/weight), respectively, na = not applicable.

Table 2. Economic returns from black soldier fly (BSF) production using biochar and gypsum amended rearing substrates.[1,2]

Rearing substrates	Cost of rearing substrate as % of production costs	Larval yield (kg)	Frass fertiliser yield (kg)	Income from BSF larvae (USD)	Income from BSF frass fertiliser (USD)	Gross income (USD)	Income from frass fertiliser as % of gross income (%)	Net income per Mg of rearing substrate (USD)	
								Substrate purchased & transported	Zero cost on substrate
BSF farming for larvae production only									
BSG	89.6	34.6	na	31.1	na	31.1	na	-232.6	37.9
BSF farming for larvae and frass fertiliser production									
BSG	87.2	34.6	585	31.1	175.4	206.5	84.9	-64.7	171.7
BSG+5gypsum	88.2	36.3	696	32.6	208.9	241.6	86.4	-53.9	182.5
BSG+10gypsum	89.1	31.7	802	28.6	240.6	269.2	89.3	-50.6	185.6
BSG+15gypsum	89.9	26.1	878	23.5	263.4	286.9	91.8	-56.8	179.6
BSG+5bicohar	87.9	41.4	633	37.3	190.0	227.2	83.6	-60.5	175.9
BSG+10biochar	88.5	53.6	696	48.3	208.9	257.2	81.2	-47.1	189.3
BSG+15biochar	89.1	63.4	759	57.1	227.7	284.8	80.0	-36.0	200.4
BSG+20biochar	89.7	64.9	876	58.4	262.8	321.1	81.8	-16.1	220.3

[1] Costs of production: BSG = 0.0522 USD/kg, biochar = 0.3 USD/kg, gypsum = 0.48 USD/kg, labour = 1.25 USD/hour. Sources of revenue: BSF larvae = 0.9 USD/kg, frass fertiliser = 0.3 USD/kg.

[2] BSG = brewery spent grains, 5gypsum, 10gypsum and 15gypsum = amendment of BSG with gypsum powder at inclusion rates of 5, 10 and 15% (weight/weight), respectively, 5biochar, 10biochar, 15biochar and 20biochar = amendment of BSG with inclusion rates of 5, 10, 15 and 20%(weight/weight) gypsum respectively, na = not applicable.

20% sawdust (Table 1), 10% gypsum, or 20% biochar (Table 2) was higher than income obtained using an unamended substrate, substrate amendment is recommended for higher profit margins. Thus, such innovations in BSF rearing have the potential for maximising profits from BSF farming and improving the sustainability of insect farming as a business (Van Huis, 2013).

Economic gains of maize production using frass fertiliser

Maize production using mineral fertiliser generated higher net maize income than the frass fertiliser and commercial organic (SAFI) fertilisers (Table 3). The findings are consistent with previous studies that reported higher net income in mineral fertiliser treated maize than organic fertilisers (Mucheru-Muna *et al.*, 2014). This could be partly attributed to higher labour costs during manure application. The net maize income generated using 30 and 60 kg N/ha of frass fertiliser was higher than those achieved using equivalent commercial organic fertiliser rates by 29 and 44%, respectively. A benefit-cost ratio (BCR) of 1.5 at 30 kg N/ha of frass fertiliser indicates the profitability of producing and utilising frass fertilisers (Table 3). The results suggest that it is less profitable to apply BSF frass fertiliser at higher than 30 kg N/ha.

Considering a farmer who produces their frass fertiliser and uses it for maize production, the net income would increase by 30, 67, and 232% for maize grown using 30, 60, and 100 kg N/ ha, respectively, compared to purchasing the same frass fertiliser (Table 4). This production system also resulted in higher BCR, return on investment (ROI), and profit margins than growing maize using urea fertiliser compared to when BSF frass fertiliser is purchased. Our results are consistent with other researchers who established that proper utilisation of organic resources could boost crop productivity (Rusinamhodzi *et al.*, 2013, 2016). Using homemade frass fertiliser would contribute to a circular economy concept, whereby the frass from BSF farming is converted into organic fertiliser for use in crop fields. Such innovative approaches can improve farm productivity through the sustainable use of available resources (Vanlauwe *et al.*, 2014).

Economically optimum frass fertiliser rate for maize production

The lower optimum N rate achieved using frass fertiliser (79 kg N/ha) (Figure 3A-C) implies that one would incur less fertiliser expenses while using frass fertiliser for maize production compared to urea (100 kg N/ha) and commercial organic fertiliser (120 kg N/ha) where higher costs would

Table 3. Economic returns from maize production if black soldier fly (BSF) frass fertiliser is bought at the same price as the commercial organic fertiliser.[1,2]

Fertiliser treatments	Grain yield (kg/ha)	Gross income (USD)	Net income (USD)	Benefit-cost ratio	Return on investment (%)	Gross margin (%)
30N FF	5,077	2,038	1,233	1.5	153.3	60.3
60N FF	5,768	2,324	1,091	0.9	88.4	46.4
100N FF	5,937	2,417	548	0.3	29.3	22.3
30N SAFI	4,048	1,635	959	1.4	141.8	57.8
60N SAFI	4,242	1,733	757	0.8	77.5	42.8
100N SAFI	4,809	1,952	756	0.4	41.9	29.1
30N UREA	4,481	1,836	1,425	3.5	346.4	76.9
60N UREA	5,039	2,035	1,589	3.5	355.9	77.8
100N UREA	5,588	2,242	1,748	3.6	354.3	77.8

[1] Cost of production: urea = 0.54 USD/kg, SAFI = 0.3 USD/kg, maize seed = 1.8 USD/kg, labour = 1.25 USD/hour. Sources of revenue: maize grain = 0.37 USD/kg, maize stover = 0.0221 USD/kg.

[2] 30N, 60N and 100N = application rates equivalent to 30, 60 and 100 kg N/ha, respectively, FF = frass fertiliser, SAFI = commercial organic fertiliser, urea = commercial mineral N fertiliser, N = nitrogen

Table 4. Economic returns from maize production if black soldier fly (BSF) frass fertiliser is directly used on the farm.[1]

Frass fertiliser rates (kg N/ha)	Net income (USD)	Benefit-cost ratio	Return on investment (%)	Gross margin (%)
30	1,598	3.63	363	78.3
60	1,819	3.61	361	78.1
100	1,817	3.03	303	75.0

[1] Production costs: labour = 1.25 USD/hour. Sources of revenue: maize grain = 0.37 USD/kg, maize stover = 0.0221 USD/kg.

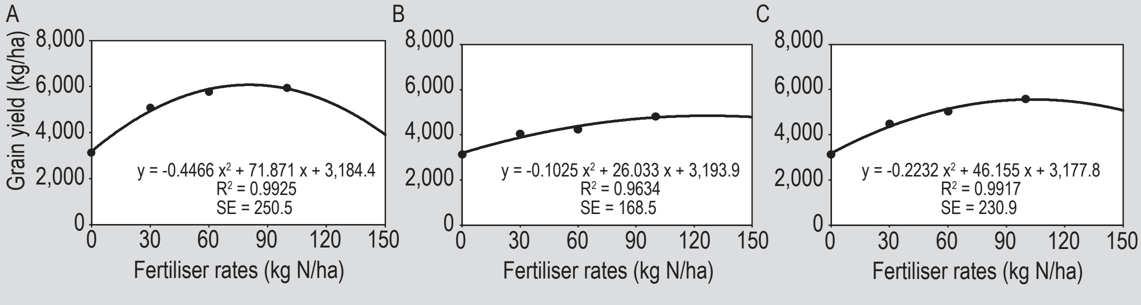

Figure 3. Yield response curves used to determine economically optimum rates of (A) frass fertiliser, (B) commercial organic fertiliser and (C) urea. Note: in a perfect market, frass fertiliser should be sold at higher price because of its higher productivity. SE = standard error.

be incurred to purchase the higher quantities of fertilisers required. The results of optimum economic rates were higher than the rates which gave the highest net profits, returns on investment, and gross profit margins because the model used to determine optimum yields only considers the cost of fertiliser (Bachmaier and Gandorfer, 2012; Naher *et al.*, 2011) and does not take into account the other costs of maize production such as labor.

The results of the stochastic dominance analysis (Figure 4) indicate that for all fertilisers, grain yield cumulative distribution with frass fertiliser is to the right of yield

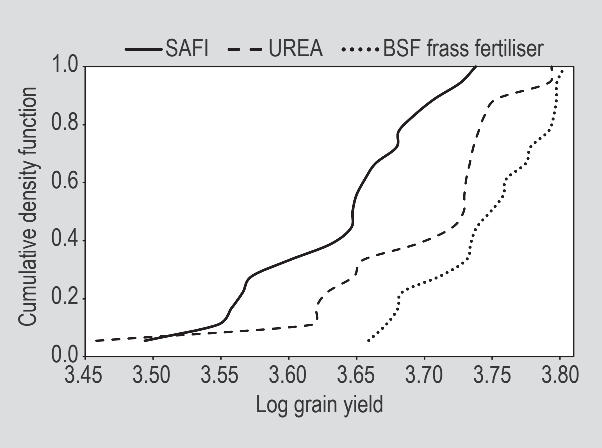

Figure 4. Stochastic dominance analysis of impact of black soldier fly (BSF) frass fertiliser on maize production. SAFI = commercial organic fertiliser, urea = commercial mineral N fertiliser.

distributions of SAFI organic fertiliser and urea fertiliser, implying that yield with frass fertiliser holds first-order stochastic dominance over those from SAFI and urea treated plots. This, therefore, indicates that compared to SAFI and urea, the application of frass fertiliser produced higher maize grain yields. Therefore, frass fertiliser could be a complete or partial substitute to the scarce yet low-quality organic resources used in most sub-Saharan African countries (Ndambi *et al.*, 2019).

The yield distribution from plots amended with urea fertiliser dominated yield distributions of SAFI, an indication that the use of urea fertiliser produces significantly (difference = 0.67; P=0.01) higher grain yields than the commercial organic fertiliser as indicated by results of the two-sample Kolmogorov-Smirnov test. However, grain yield distributions from plots treated with BSF frass fertiliser and urea fertiliser did not vary significantly (difference = 0.39; P=0.131). Findings from the present study are crucial in reducing heavy reliance on expensive mineral fertilisers by adopting high-quality organic fertilisers such as BSF frass fertiliser.

4. Conclusions

This study provides the first report on the circular economy of BSF farming. It demonstrates that unless feedstock for rearing BSF is available on-farm, the profit margins might be limited due to purchase and transportation costs. The combination of insect-based frass organic fertiliser and animal feed provided higher economic benefits. This can improve smallholder farmers' food security and livelihoods. Findings showed that the utilisation of frass fertiliser for maize production would further attract higher profitability than existing commercial organic fertilisers. In addition to the direct economic benefits, social and environmental services of BSF framing will further increase the benefits of insect farming. Thus, scaling up insect-based feed and frass fertiliser sustainable and innovative technologies would require more research on quantifying the economic feasibility and social-environmental services of BSF farming across different production systems.

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Conflict of interest

The authors declare no conflict of interest.

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