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Samenvatting NL Zwarte soldaten vliegen (ZSV) kunnen een belangrijke rol spelen in een circulaire economie, door hun vermogen om diverse vormen van reststromen en bijproducten om te zetten in eiwitrijke veevoer ingrediënten. In deze studie zijn de milieu effecten en mogelijkheden om zwarte soldaten vliegen te kweken in Kampala, Uganda onderzocht. Met toepassing van een Life Cycle Assessment (LCA) zijn de belangrijkste emissie punten in het productie proces in kaart gebracht. De gekozen systeemgrenzen liepen van ontstaan van afval via productie van de larven tot en met de post-productie fase. De functionele eenheid was een kg gedroogde larven. Om de resultaten vergelijkbaar te maken met andere onderzoeken, zijn kilogrammen eiwit en kilogrammen organisch materiaal als additionele functionele eenheden beschouwd. De inventarisatie is gebaseerd op achtergrond informatie vanuit Ecoinvent v 3.4 and verdere data vanuit de ZSV productie eenheid. De milieu impact is beoordeeld op global warming potential (kg CO2eq). Behalve emissies vanuit de ZSV eenheid zijn drie andere vermeden emissies opgenomen, i) door verminderde storting van afval op stortplaatsen, ii) het niet geproduceerde veevoer dat vervang dat vervangen is door ZSV producten en iii) verminderde productie van kunstmest door gebruik van frass (insecten mest) als organische meststof. De resultaten tonen aan dat de productie van een kg larven 3.1 kg CO2eq uitstoot, wat neerkomt op 8.2 kg CO2eq per kg eiwit. De grootste bijdrage aan emissie vanuit de productie eenheid kwam van energie gebruik en transport. De resultaten tonen aan dat de productie van een kg ZSV larven 9.7 kg CO2eq voorkomt door verminderde emissie uit stortplaatsen, vervanging van veevoer ingrediënten en vervanging van kunstmest. De grootste vermeden emissie komt van de stortplaatsen, wanneer het afval gebruikt wordt voor ZSV productie (5.1 kg CO2eq per kg gedroogde larven) waarmee de aanvoer van soja vermeden kan worden. In vergelijking met andere studies is de vermeden CO2 emissie lager, wat een gevolg is van bioconversie van ZSV larven die bij het bedrijf van deze studie in de opstartfase nog relatief hoog is. Het verbeteren van de efficiëntie van het productieproces (snellere groei van de larven) en het verminderen van transport afstanden vormen de belangrijkste verdere bijdragen aan het milieu voordeel van ZSV productie. Gebaseerd op deze resultaten kan de conclusie getrokken worden dat de ZSV kan bijdragen aan een significante emissie verlaging bij het produceren van veevoer ingrediënten.

Summary UK This study was carried out to assess the environmental impacts of black soldier fly larvae (BSFL) in a production unit of Marula agribusiness located in Kampala, Uganda. Life cycle assessment was applied to identify the hotspots of the greenhouse gas (GHG) emissions in the larvae production process. Both environmental burdens and benefits were determined. The obtained results showed that production of one kg dried larvae emits 3.1 kg CO2eq while it prevents 9.7 kg CO2eq. Due to avoiding emissions from landfill, replacing livestock feed ingredient, and replacing chemical fertilizer. Higher GHG emissions per unit of product shows the potential for improvements in the BSFL production in research region. Our findings show positive environmental impacts of BSFL products to feed livestock. Increasing the efficiency of rearing process (by increasing the larvae growth rate) and reducing the transportation distance can be considered as the options to reduce the environmental impacts of BSFL production.

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Foreword

The interest for insects as a sustainable ingredient for animal feed is growing strongly. Using insects, especially Black Soldier Flies, to process low value biomass can potentially lead to significant environmental gains in terms of e.g. reduced dumping it as waste on landfills.

For a wider assessment of the sustainability of BSF production, more insight into nutrient bioconversion efficiencies and nutrient losses via gaseous emissions is needed. Gases such as of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3), are of particular interest due to the negative impact that these have on the global climate, air quality and eutrophication. Very little research has actually been carried out so far.

This Seed Money Project is a first attempt to estimate the environmental impacts of BSFL production by calculating the amount of the GHGs emitted in the whole production process. It needs to be followed by more intensive on-site research activities in future to be able to fully appreciate the sustainability of Black Soldier Fly production.

Adriaan Vernooij

Project leader Seed Money Project Insect oil as a high-quality animal feed ingredient in Uganda

Summary

The black soldier fly larvae (BSFL) can play a role in promoting a circular economy via efficient use of resources in the food chain and acting as a protein-rich feed ingredient for the livestock and aquaculture sectors. In this study we assessed the environmental impacts and opportunities of rearing BSFLs in a production unit of Marula agribusiness located in Kampala, Uganda. Life cycle assessment (LCA) was applied to identify the hotspots of the greenhouse gas emissions (GHG) in the larvae production process. The system boundaries were from the cradle to the BSFL processing unit gate, including the larvae production phase and related upstream activities, and the post-production phase. The functional unit (FU) was one kg dried larvae. To make the results comparable with the other research, kg protein and kg organic waste were also considered as additional FUs. The inventory was based on background data sourced from the Ecoinvent v 3.4 and foreground data provided by the production unit. The environmental impacts were assessed considering global warming potential (kg CO_2eq). Besides emissions from BSFL production, three sources of avoided emissions were considered in this study through system expansion, including i) avoiding dumping of organic waste in landfills, by using it as substrate in the larvae production process; ii) avoiding production of livestock feeds, by feeding BSFL as livestock feed, and iii) avoiding production of chemical fertilizer by using BSFL manure/frass as an organic fertilizer. The results showed that production of one kg dried larvae emits 3.1 kg CO_2eq., equal to 8.2 kg CO_2eq when expressed per kg protein in the larvae. Energy contributed most to the total emissions from production, followed by transport. Results also showed that production of one kg dried BSFL could prevent 9.7 kg CO_2eq due to avoiding emissions from landfill, replacing livestock feed ingredient, and replacing chemical fertilizer. The largest reduction in GHG was due to avoiding landfilling of organic waste (5.1 kg CO_2eq per kg dried larvae) and replacing the commonly used animal feed components (soybean meal) by BSFL. Compared to the previous studies the carbon footprint in the present study was higher, which mainly relates to lower feed conversion rate of larvae. Increasing the efficiency of rearing process (by increasing the larvae growth rate) and reducing the transportation distance can be considered as the options to reduce the environmental impacts of BSFL production. Based on the obtained results it is concluded that there is a high potential to reduce the GHG emissions of food production by replacing the commonly used feed components by BSFL.

1 Introduction

It is expected that in order to feed the 9.7 billion people in 2050, the global food demand increases by 70% by the year 2050 compared to 2005 (Tilman *et al.*, 2011). At the same time, climate change is one of the biggest threats faced by humanity over the next decade. The challenging task of food production sectors is assuring food security while the planetary boundaries are considered. In recent years, due to changes in human diet, the use of more animal-based foods (milk, meat, fish and eggs) increased.

Based on the World Bank data, the average population growth in Sub-Saharan Africa is around 2.7%. Despite the increase in population, the agricultural production is still relatively low in Sub-Saharan Africa. This shows the importance of increasing agricultural productivity in this region. Livestock production currently accounts for about 30% of the gross value of agricultural production in Africa (Shumo *et al.*, 2019). Poultry and pig sectors play an important role in providing the demand for animal-based food. Uganda is known as a low-income country with a gross domestic product (GDP) per capita of around 600$ and agriculture is the main driver of the development in this country. The agriculture sector contributes around 25% of the GDP and around 71% of employments occurs in this sector. The share of livestock farming within the agriculture sector is around 17%. The largest livestock population belongs to chickens and followed by goats, cattle and pig. In recent years lots of attempts have been started by government for developing the livestock sector. However, one of the barriers against the development is animal feed availability.

Livestock is an important contributor to the climate change. The main greenhouse gases (GHGs) in livestock sector are methane (CH_4) from enteric fermentation and animal manure, N_2O from manure and slurry management and feed production, and CO_2 from land use changes (feed production) and fossil fuel usage. Feed production (including land use and land use change) is a main driver of environmental impact of livestock production and around 40% of GHG emissions in livestock sector belongs to feed production (Gerber *et al.*, 2013). Therefore, considering alternative sources of animal feeds with lower environmental impacts are proposed as a GHG mitigation option in livestock sectors. In addition, alternative sources of animal feeds can potentially result in less food-feed competition and reduction of production costs of animal-based foods in Africa. To sum it up, due to the potential positive impacts of alternative sources of animal feeds on environmental, economic and social aspects, it might lead to a more sustainable production.

The black soldier fly larvae (BSFL) is recognized as promising alternative source of animal feed. BSFLs use organic waste substrates such as coffee bean pulp, vegetables residues, catering waste, municipal organic waste, straw, and fish offal, and turn them into high protein biomass (Shumo *et al.*, 2019). BSFL contains high levels of protein (37–63%) and fat (20–40%) (Schiavone *et al.*, 2017; Roos, 2018) and it's production process might result in lower level of emissions compared to other sources of protein such as crops because of using more waste materials as input and less (or no) resources such as land, fuel, fertilizers, etc.. Moreover, BSFL is a good source of minerals such as calcium, iron, potassium, magnesium, phosphorus and zinc as well as vitamins including niacin, vitamin B12, thiamine and riboflavin (Spranghers *et al.*, 2017; Chia *et al.*, 2019).

In addition to economic aspect, the environmental impact is considered as one of the important aspects of the insect production. To have a better insight in the environmental impacts of insect production, the assessment needs to be conducted through the whole life cycle of the production system and needs to be compared with the commonly used animal feed components they can replace. To assess the environmental impacts, life cycle assessment (LCA) methodology is applied, where the impact is quantified through the entire chain, where both direct and indirect emissions are determined. Direct emissions refer to emissions that are emitted due to the metabolism of insects or anaerobic fermentation and also application of inputs in the rearing process of larvae. Indirect emissions are related to production of inputs that are used in the larvae production process.

BSFL production as an alternative source of animal feed protein received considerable attention. Many research projects have studied replacing commonly used animal feed components by insect products (Iaconisi *et al.*, 2017; Onsongo *et al.*, 2018; van der Fels-Klerx *et al.*, 2018; Biasato *et al.*, 2019), digestion of different types of waste using insects (Beskin *et al.*, 2018) and efficiency of bioconversion plants (Jiang, 2018; Li *et al.*, 2018). However, few studies used LCA to determine the environmental impacts of BSFL production.

Bava *et al.* (2019) showed that the use of by-product for feeding larvae is a useful approach to reduce the environmental impacts of BSFL protein. They evaluated the growth performance, nutrient composition, and environmental impact of BSFLs reared on hen diet and by-products diets (okara, maize distillers, and brewer's grains). They found that the rearing substrate has impact on the larvae growth performance, environmental impact and the nutrient value. The results showed the higher growth rate of larvae fed on a hen diet and the maize distiller exhibited. The lipid content of the larvae and the larvae diets was correlated. Feed production contributed most to the total environmental impacts of rearing insect and high inclusion of soybean meal was the most impactful for the environmental impacts (5.79 CO_2eq per kg dry larvae). The carbon footprint (CF) of larvae fed by maize distillers, okara and brewer's grains were 1.95, 0.68 and 0.81 kg CO_2eq per kg dry larvae, respectively.

Guo *et al.* (2021) studied material flow and environmental impacts of a food waste bioconversion plant using BSFL. The results of material flow showed that around 6% of the food waste was transformed into BSFL, 51% was stored in produced compost, and 43% was released as gasses to the air. Environmental assessment showed that on average the global warming potential (GWP) impact of BSFL production is 17.36 kg CO_2eq per ton food waste.

In an LCA study conducted by Smetana *et al.* (2016) the environmental impacts of insect production at industrial level were assessed and results showed that the environmental benefits were 2-5 times larger than the commonly used feed products. The conducted LCA considered the emissions associated with the production of inputs (e.g. electricity and heat), however, the emissions produced during the rearing process were not considered.

Mertenat *et al.* (2019) determined the GHG emissions of BSFL treatment facility using LCA methodology and compared it with the open windrow composting facility. Results showed that the direct emissions are 47 times lower the emissions from composting facility. The main GWP contributors were: i) residue post-composting and ii) electricity needs and source.

Bosch *et al.* (2019) carried out a literature study to evaluate the impact of 78 mixtures of resources (feed and food materials, residual streams, and animal manure) on rearing of Black Soldier Fly Larvae (BSFL). The environmental results showed that resources within the legal groups (i.e. A and B1 in EU regulation No 68/2013) that are, at the moment, not allowed in EU as animal feed had a lower GWP. Results showed that BSFL reared on a resource that contains food (e.g. sorghum) and feed (e.g. dried distillers grains with soluble) products had higher environmental impacts (per kg protein basis) than the conventional feed protein sources (such as fishmeal and soybean meal). As a general finding they showed that there is a high potential to reduce the environmental impacts of food production by replacing typical feed components with the insect products.

Maiolo *et al.* (2020) carried out an LCA to compare the environmental impacts of four alternative protein sources (poultry by-product meal, insect meal, dry microalgae biomass from Tetraselmis suecica, and dry microalgae biomass from Tisochrysis lutea) to feed animals. The results showed the higher environmental impacts for drymicroalgae biomass (48.36 and 38.43 kg CO_2eq per kg protein contained in the meal for Tetraselmis suecica and Tisochrysis lutea, respectively) compared to poultry by-product meal (5.38 kg CO_2eq per kg protein contained in the meal) and insect meal (2.05 kg CO_2eq per kg protein contained in the meal).

Although economic aspects of insect production have been studied in Africa, to our knowledge no study has focused on the environmental impacts of insect production in Africa. Therefore, this study aimed to conduct an LCA for BSFL production using data from a production unit of Marula agribusiness located in Kampala, Uganda. Besides estimating GHG emissions of BSFL production, potential reduction of GHG emissions by replacing commonly used animal feed components with insect proteins is assessed.

2 Material and methods

To quantify the GHG emissions of BSFL production, the LCA methodology was applied and both direct and indirect emissions were estimated. To conduct the LCA, four phases need to be defined namely goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. All these phases or steps will be discussed in detail in the following sections.

2.1 Goal and scope

The goal of the current LCA was estimating the environmental impacts of BSFL production process by calculating the amount of the GHGs emitted in the whole production process. To have a better insight, both positive and negative environmental impacts were considered. The negative impact is due to all the emissions produced during the production process (off- and on-farm emissions) while positive impact refers to avoided emissions due to: i) using organic waste in the BSFL production process instead of dumping the organic waste in landfills, ii) replacing commonly used feed components by BSFL products, and iii) using larvae manure/frass to replace the chemical fertilizers. The negative and positive impacts will be discussed in detail in the LCI section.

The system boundaries of the current LCA are presented in Figure 1.2. The BSFL production system consists of different process stages: collecting and processing of organic waste, rearing larvae, and processing of harvested larvae (drying and oil extraction). After the organic wastes are collected and transported to the BSFL production unit, they are shredded to small particle, mixed and added to the crates as the substrate in the rearing process. Shredding and mixing helps the larvae to feed better. The rearing larvae stage includes four growing stages namely egg, larvae, pupa and adult. Due to the fact that whole cycle of BSFL production occurs in the same unit therefore, the larvae rearing process consists of producing neonates (from adult flies) and rearing neonates. At the end of rearing process, the larvae are collected and dried. Dried larvae are sent to the oil extraction unit and the final products (press cake and BSFL oil) are packed. The press cake and oil are the final products, and the BSFL manure/frass is a by-product of raring process which is used as an organic fertilizer. Electricity is the main source of energy in the BSFL production unit. Electricity generation capacity in Uganda is dominated by the hydropower and supported by the heavy fuel oil and biomass cogeneration power plants. In most of Sub-Saharan African countries electricity production relies on hydropower. Starter is another input which is a protein rich feed ingredient and is fed to neonates at the first days of rearing period. To pack the final products, the woven sacks were used.

The functional unit (FU) of one kg of final product (press cake + BSFL oil) was used to report the results of the LCA, using system boundaries from cradle to production unit gate. To make the results of this study comparable with the former studies, the results of GHG emissions will also be presented per kg of organic waste and per kg protein.

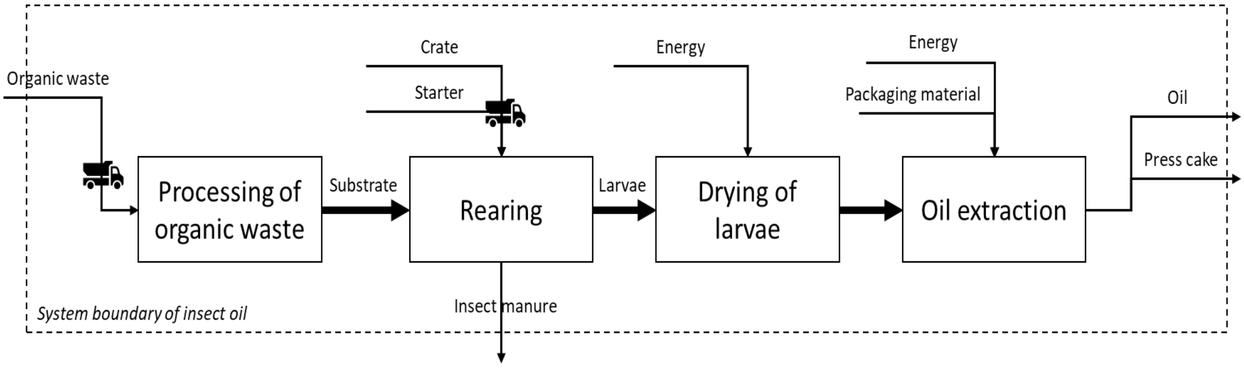

Figure 1.2 *System boundaries of black soldier fly production process.*

In a process in which more than one product is produced, it is essential to partition the environmental burdens to the products and co-products. Based on ISO 14044 (2006) it is suggested to use system expansion whenever possible and where it is not possible to use system expansion, allocation can be used instead. Therefore, we used system expansion, considering the environmental impact of chemical fertilizers which can be replaced by BSFL manure/frass. Avoided emissions from landfill and commonly used animal feed were also considered in this study which will be discussed in the next sections. The avoided emissions were considered as the environmental benefits of BSFL production system.

2.2 Life cycle inventory

2.2.1 Production emissions (direct and indirect)

To calculate the GHGs emitted during the production of the BSFL, direct (on-farm) and indirect (off-farm) emissions were calculated using foreground and background data. Foreground data include all the data related to BSFL production in the production unit such as the mass of consumed inputs (e.g. organic waste, electricity, diesel and etc.) while background data consist of emissions associated with the production of a unit of inputs consumed in the production process. Foreground data were collected from a production unit (Marula agribusiness located in Kampala, Uganda) and are presented in Table 1. Due to the fact that larvae feeding material are considered as waste, no emissions were assigned to them. Based on the collected data, around 21.1 kg total organic waste are used to produce one kg dried BSFL. Transport consists of transporting organic waste and starter (including spent grain and expired fish feed or maize bran) to the BSFL production unit. Total energy use for shredding, mixing and separation was 0.7 kWh per FU. The energy consumption was calculated diving the nominal power of machinery by its capacity. The main product of rearing process is larvae while the BSFL manure is the co-product. At the end of rearing process, larvae are sent to the drying unit for further processing. Finally, under pressure the oil is extracted from the dried larvae. The BSFL oil and press cake are the final products. The mass fraction of oil in dried larvae was 20% with the remaining press cake of 80%.

Table 1 *Life cycle inventory for the BSFL production process.*

Process	Item	Unit	Amount (unit per FU)
Rearing	A. Inputs		
	Rearing substrate (organic waste)	kg/FU*	21.1
	Transport (organic waste and starter)	t.km/FU	0.9
	Energy (shredding, mixing and separation)	kWh/FU	0.7
	Crate	kg/FU	2.4
	Starter	kg/FU	1.7
	Neonates	kg/FU	0.1
	B. Outputs		
	Larvae	kg/FU	2.5
	BSFL manure/frass	kg/FU	3.7
Processing of products	A. Inputs		
	Energy (drying and oil extraction)	kWh/FU	1.4
	B. Outputs		
	Press cake	kg/FU	0.8
	Extracted oil	kg/FU	0.2
Rearing	A. Inputs		
	Rearing substrate (organic waste)	kg/FU*	21.1
	Transport (organic waste and starter)	t.km/FU	0.9
	Energy (shredding, mixing and separation)	kWh/FU	0.7
	Crate	kg/FU	2.4
	Starter	kg/FU	1.7
	Neonates	kg/FU	0.1
	B. Outputs		
	Larvae	kg/FU	2.5

* FU is 1 kg of dried larvae (the mass fractions of press cake and extracted oil is 80% and 20%, respectively).

Background data were extracted from Ecoinvent database version 3.4 (Wernet *et al.*, 2016). The details of applied background data are presented in Table 2. Given that the age of transport vehicle and quality of roads have significant impact on the transport emissions, and because of lack of data the emission factors were adopted to the real situation in Africa. Therefore, we applied the higher emission factors (two times higher) in calculations compared the value presented in Table 2. For the emissions associated with the transport it was assumed that the truck has a one-way load, thus they travel back empty. Given the high lifetime of machineries (mixer, dryer, etc.) and crates, the emissions per FU was negligible. Therefore, we ignored it in our environmental assessment. The emission factor for drying of larvae was extracted from Ecoinvent database version 3.4 (Wernet *et al.*, 2016), where the GHG emissions per kg of water evaporated has been determined. To calculate the avoided emissions of replacing chemical fertilizers by the BSFL manure, we applied the emissions associated with the production of one kg of nitrogen, phosphorus oxide (P_2O_5) and potassium oxide (K_2O) (Table 2). Due to the lack of data, the emissions associated with the application of the BSFL manure in soil were not considered in this study.

Table 2 *The GHG emissions associated with the production of inputs and operations (background data).*

Process	Item	Unit	Amount (unit)	Reference
Transport		kg CO_2eq/t.km	0.21	(Wernet *et al.*, 2016)
Electricity		kg CO_2eq/kWh	0.51	
Energy	Energy for drying	kg CO_2eq/kg water	1.64	(Wernet *et al.*, 2016)
Mineral fertilizer	General fertilizer (Nitrogen)	kg CO_2eq/kg nutrient	3.98	(Pishgar-Komleh *et al.*, 2020)
	General fertilizer (P_2O_5)	kg CO_2eq/kg nutrient	2.03	(Pishgar-Komleh *et al.*, 2020)
	General fertilizer (K_2O)	kg CO_2eq/kg nutrient	1.05	(Pishgar-Komleh *et al.*, 2020)

The results of Parodi *et al.* (2020) study showed that the direct emissions of the BSFL production can be 16.8 ± 8.6 g CO_2eq per kg of dry BSFL. The emissions consist of methane and nitrous oxide which are emitted during rearing of larvae. We considered 20.8 g CO_2eq per kg of dry BSFL as the direct emissions.

2.2.2 Avoided emissions (landfill)

One of the environmental advantages of rearing the BSFL is using organic waste in the production process of a product instead of dumping it in the landfill. One of the assumptions behind our calculations was that almost all of organic materials used for feeding the BSFLs are not used in the production of other products and they are dumped in landfills. The environmental burdens of dumping organic waste in the landfill were determined and considered as the avoided emissions if the organic waste is used in the production process of the BSFL. Both CH_4 and CO_2 are emitted in the landfills. Due to the fact that the CO_2 emitted from the landfill site is not fossil derived and naturally is recycled by the plants, it is a part of natural CO_2 cycle (Buratti *et al.*, 2015). Therefore, we did not consider it as a source of the GHG emissions.

To calculate the CH_4 emissions due to application of organic waste in landfill, Tier 1 of IPCC (2006) approach was applied using the following equation:

$$CH_4 \text{ emissions } (Gg/y) = [(MSW_T \times MSW_F \times L_0) - R] \times (1 - OX) \qquad \textit{Eq. 1}$$

where MSW_T is the total municipal solid waste generated (Gg/y), MSW_F is the fraction of MSW disposed at solid waste disposal sites (SWDS), and *R* is the recovered CH_4 (Gg/y). Methane recovery is the amount of CH_4 generated at SWDS that is recovered and burned in a flare or energy recovery device. Since no gas is recovered in the landfill in the research area, the value of zero was used for the methane recovery. *OX* denotes oxidation factor (in fraction). The oxidation factor (OX) reflects the amount of CH_4 from SWDS that is oxidised in the soil or other material covering the waste. The default oxidation factor in the IPCC Guidelines is zero. However, results from the field and laboratory tests suggests an average value less than 0.1. The last parameter in the upper equation is L_0 which is the methane generation potential and calculated as follows:

$$L_0 (Gg\ CH4/Gg\ waste) = MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \qquad \textit{Eq. 2}$$

where *MCF* is methane correction factor (fraction). Based on IPCC (2006), MCF of 0.4 was used in this study because the landfill site was classified as unmanaged – shallow (<5 m waste). DOC_F is an estimate of the fraction of carbon that is ultimately degraded (Degradable organic carbon) and released from *SWDS* and reflects the fact that some organic carbon does not degrade, or degrades very slowly, when deposited in SWDS. The IPCC guidelines provide a default value of 0.77 for DOC_F however, based on recent literature, the default value might be 0.5-0.6 (IPCC, 2006). We applied 0.55 in this study. *F* indicates the fraction by volume of CH_4 in landfill gas. Landfill gas consists mainly of CH_4 and CO_2. The CH_4 fraction can vary between 0.4 and 0.6, depending on several factors including waste composition (e.g. carbohydrate and cellulose). *DOC* is the degradable organic carbon [fraction (Gg C/Gg MSW)]. DOC for the waste stream was estimated using Eq. 3 and Table 3. Since organic waste is the only waste is used for feeding neonates, we ignored the A, B and D types of waste and just considered C type of waste.

$$DOC = (0.4 \times A) + (0.17 \times B) + (0.15 \times C) + (0.3 \times D) \qquad \textit{Eq. 3}$$

Table 3 *Default degradable organic carbon values for various waste streams (Srivastava and Chakma, 2020).*

Waste stream	degradable organic carbon (% by weight)
A [Paper and textiles]	40
B [Garden and park waste, and other organic putrescible]	17
C [Food waste]	15
D [Wood and straw waste]	30

2.2.3 Avoided emissions (alternative source of protein)

Another environmental advantage of rearing the BSFL is replacing the commonly used animal feed components (e.g. soybean) by the BSFL products. To estimate the environmental impacts, first it is necessary to calculate the substitution rate. To calculate the substitution rate, crude protein content of dried larvae as reported by Shumo *et al.* (2019) was compared with the commonly used animal feed component. Given that depending on the substrate material the composition of produced larvae might be different; an average value of chicken manure fed the BSFL, kitchen waste fed the BSFL and spent grain fed the BSFL was calculated for composition of produced BSFL (Table 4).

Table 4 *Composition of produced black soldier fly larvae reared in different substrate. (DM=Dry Matter; OM=Organic Matter; CP= Crude Protein; NDF=Neutral Detergent Fiber; ADF=Acid Detergent Fiber; EE=Ether Extract; CM=Chicken Manure; KW=Kitchen Waste; SG=Spent Grain) source:(Shumo et al., 2019).*

Parameters	**Chicken Manure fed BSFL (g/kg DM)**	**Kitchen Waste fed BSFL (g/kg DM)**	**Spent Grain fed BSFL (g/kg DM)**	**Average (g/kg DM)**
Dry Matter	80.7	87.7	83.1	838.3
Ash content	9.3	9.6	11.6	101.7
Organic matter	59.8	90.4	88.4	795.3
Crude protein	41.1	33	41.3	384.7
NDF	21.9	20.4	28.6	236.3
ADF	12.6	13.2	15	136.0
Ether extract	30.1	34.3	31	318.0

Table 5 shows the composition of most commonly used animal feed components (as a source of protein in the research area) compared to the BSFL. CVB (2019) was used to extract the chemical composition and the nutritional values of the feedstuffs and the substitution rate was calculated using crude protein (CP). The GHG emissions associated with the production of feed components was calculated using FeedPrint tool (Vellinga *et al.*, 2013). After calculating the substitution rate and the CF, the avoided emissions due to replacing various feed components by BSFL was estimated. The avoided emissions were considered as the environmental benefit of rearing the BSFL. In this study we assumed that the BSFL will replace the soybean meal, therefore the average avoided emission of 2,336 kg CO_2eq per ton BSFL was assumed for further assessments.

Table 5 *Composition, substitution rate and carbon footprint of produced black soldier fly larvae and commonly used animal feed.*

Item	**DM (g/kg)[1]**	**CP (g/kg)[1]**	**NDF (g/kg)[1]**	**ADF (g/kg)[1]**	**Substitution rate (kg)**	**Feed production (kg CO_2eq /ton soy)**	**Land use change (kg CO_2eq /ton soy)**	**Carbon footprint (kg CO_2eq /ton soy)[2]**	**Avoided emission (kg CO_2eq /ton BSFL)**
Black soldier larvae	838	384	236	136	1000				
Soybean expeller	916	439	131	85	876	528	4,060	4,588	4,020
Soybean heat treated	899	362	109	52	1062	656	2,959	4,623	4,912
Soybean hulls	883	129	514	383	2981	349	2,178	4,289	12,789
Soybean hulls	886	105	559	414	3663	335	2,067	4,466	16,361
Soybean hulls	887	101	579	446	3808	329	2,021	4,257	16,213
Soybean meal	878	489	83	49	786	596	4,027	2,527	1,988
Soybean meal	880	436	131	85	882	557	3,732	2,402	2,119
Soybean meal	877	467	104	65	823	578	3,888	2,350	1,936
Soybean meal	878	421	153	102	913	553	3,704	3,615	3,303
Soybean raw	899	362	109	52	1062	652	2,959	3,611	3,837
Black soldier larvae	838	384	236	136	1000				
Soybean expeller	916	439	131	85	876	528	4,060	4,588	4,020
Soybean heat treated	899	362	109	52	1062	656	2,959	4,623	4,912
Soybean hulls	883	129	514	383	2981	349	2,178	4,289	12,789
Soybean hulls	886	105	559	414	3663	335	2,067	4,466	16,361
Soybean hulls	887	101	579	446	3808	329	2,021	4,257	16,213

[1] extracted from CVB (2019)

[2] extracted from FeedPrint tool (Vellinga *et al.*, 2013)

In additional to soybean, the BSFL products can replace fish meal in research area. Therefore, the avoided emissions of utilizing BSFL for feeding fish was estimated. Using the protein content, the substitution rate was determined. The average protein content of fish meal was assumed to be 640 (g per kg) (Wernet *et al.*, 2016) which was higher than the soybean protein content. The emissions associated with the production of fish meal was 0.85 kg CO_2eq per kg fish meal (Wernet *et al.*, 2016).

2.2.4 Avoided emissions (alternative source of soil fertilizer)

The BSFL manure is applied in arable crop production as an organic fertilizer in research area. Application of the BSFL manure reduces the application of mineral fertilizers. The nutrient value of insect manure was used to calculate the potential substitution rate. Based on the collected data, nitrogen, phosphorus and potassium content of produced manure was 5, 1 and 2 kg per 100 kg insect manure. It should be mentioned that due to lack of data, the loss of nutrients of the BSFL manure during manure storage was ignored. Moreover, it was assumed all the NPK content of manure is available for plant. The GHG emissions associated with the production of different types of mineral fertilizer were taken from Pishgar-Komleh *et al.* (2020) (Table 2), where the average GHG emissions of mineral fertilizers were calculated based on the nutrient content. Using emission factors and substitution rate, the emissions avoided due to replacing synthetic fertilizers by insect manure were calculated.

2.3 Life cycle impact assessment

For the LCIA phase and to aggregate the GHG emissions, the 100-year global warming potential (GWP) of 1, 34 and 296 CO_2-eq corresponding to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were used (IPCC, 2013).

3 Results and discussion

The GHG emissions of the whole BSFL production cycle (including emissions from rearing, transport, energy use) and the avoided emissions from organic waste, the BSF manure and soybean meal are presented in Table 6. The emissions and avoided emissions are presented per kg dried larvae and ton of organic waste (used for feeding the BSFL). As it is shown, the total emission was 3.1 kg CO_2eq per kg dried larvae while the avoided emission was 9.7 kg CO_2eq per kg final product. The results showed that the BSFL production process leads to the environmental benefits equal to 5.2 kg CO_2eq per kg dried larvae. The total GHG emission per ton of organic waste was 148.8 kg CO_2eq while the avoided emission was 462 kg CO_2eq per kg organic waste. The obtained results revealed that the BSFL has a high potential to reduce the produced GHG emissions. This reduction of the GHGs occurs by using organic waste instead of dumping in landfills, applying the BSFL manure to replace mineral fertilizers and by replacing the commonly used animal feed components (such as soybean meal). The avoided emission of organic waste, the BSFL manure and commonly used animal feed were 5.1, 0.9 and 3.8 kg CO_2eq per kg dried larvae, respectively (Table 6).

To be able to compare our results with other studies, we applied the third FU, i.e. one kg protein contained in the produced larvae. The results showed a CF of 8.2 kg CO_2eq per kg protein contained in the produced BSFL. The CF of dried larvae in our study was higher than what was found in studies by Maiolo *et al.* (2020) and Bava *et al.* (2019). Maiolo *et al.* (2020) found that the emissions associated with the production of BSFLs range between 2.05 and 4.90 kg CO_2eq per kg protein contained in the meal. According to Bava *et al.* (2019), the CFs of the production of 1 kg of dry larvae on different substrates (hen diet, maize distillers, okara, brewer's grain) are 5.76, 1.95, 0.68 and 0.81 kg CO_2eq, respectively. These CFs were equal to 12, 3.82, 1.36 and 1.53 kg CO_2eq per kg protein contained in the BSFL (Bava *et al.*, 2019). The CF of our study was closer to the CF of the BSFL fed on hen diet. The main reason for the higher CF than previous study was the lower conversion rate of organic waste to BSFLs. In addition to the low growth rate, the lower protein content, the higher energy consumption and also the higher transport emissions resulted in the higher CF of BSFLs in our study.

Table 6 *Composition of produced black soldier fly larvae reared in different substrate. (DM=Dry Matter; OM=Organic Matter; CP= Crude Protein; NDF=Neutral Detergent Fiber; ADF=Acid Detergent Fiber; EE=Ether Extract; CM=Chicken Manure; KW=Kitchen Waste; SG=Spent Grain) source:(Shumo et al., 2019).*

Item	**Emissions (kg CO_2eq/kg product)**	**Avoided emissions (kg CO_2eq /kg product)**	**Emissions (kg CO_2eq /ton waste)**	**Avoided emissions (kg CO_2eq /kg waste)**
Avoiding landfill of organic waste	0	-5.09	0	241.92
Rearing larvae	0.02	0	0.99	0
Transport	0.20	0	9.29	0
Processing larvae (energy use)	2.92	0	138.48	0
Avoiding chemical fertilizer production	0	-0.89	0	42.05
Avoiding soybean meal	0	-3.75	0	178
Total	3.13	-9.73	148.76	462

Figure 1.3 shows both emissions (red bars) and avoided emissions (green bars) of insect production process. As it is seen, use of energy to do the machinery operations (such as shredding, separation and etc.) contributed most to the total GHG emissions and followed by transport emissions and the emissions during rearing BSFL. Among the sources of avoided emissions, use of organic waste in the rearing process of larvae had the highest share (5.09 kg CO_2eq per kg final product) and followed by final product (replacing animal feed meal by BSFLs) and BSFL manure.

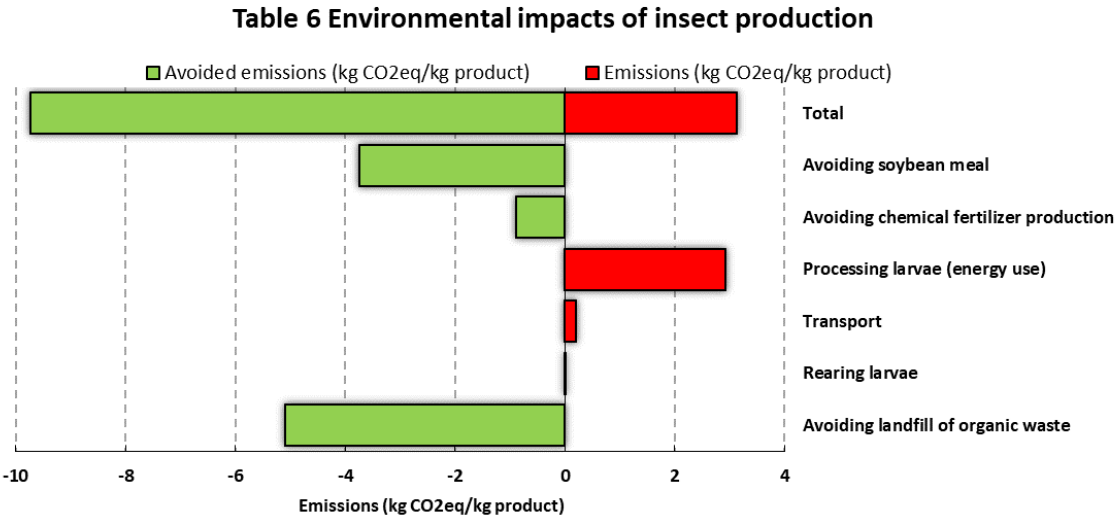

Figure 1.3 *Environmental impacts (emissions and avoided emissions) of black soldier fly larvae production.*

Besides studding the environmental impact of replacing the soybean meal by the BSFL, the impact of replacing fish meal by the BSFL was determined as well. Figure 2.3 shows the avoided emissions for two scenarios (avoided soybean meal and fish meal). Results showed that replacing fish meal by the BSFLs avoids 0.52 kg CO_2eq per kg BSFL while for the soybean meal, the avoided emissions was 3.8 kg CO_2eq per kg BSFL. The lower CF of fishmeal and the lower protein content of the soybean meal were the reasons of lower avoided emissions for replacing fishmeal by BSFLs. The protein content of soybean meal and fishmeal were 453 and 630 g protein per kg, respectively. The GHG emissions associated with the production of the soybean meal was 2.7 kg CO_2eq per kg soybean (including land use change) while production of one kg fishmeal results in 0.85 kg CO_2eq. As it has been illustrated in Figure 1.3, replacing both the soybean meal and the fish meal by BSFL have environmental benefits. However, replacing the soybean by the BSFLs is more reasonable than fish meal in terms of the environmental benefits (Figure 2.3).

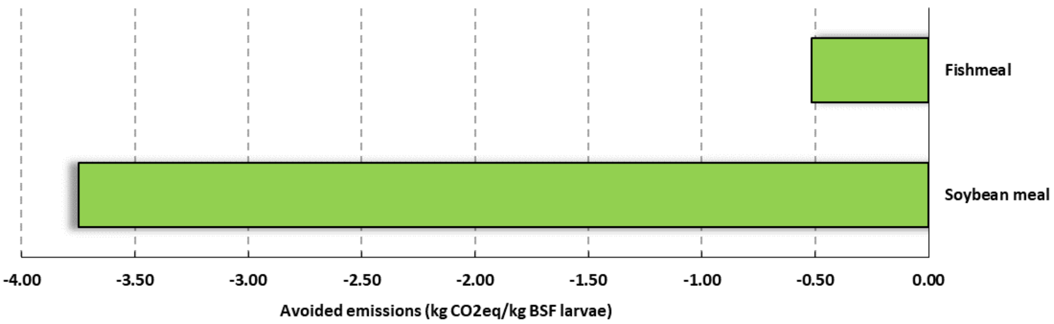

Figure 2.3 *The avoided emissions of replacing soybean meal and fishmeal by BSFL.*

BSFL has a high potential in the poultry, pig and fish feed industry. Not only it increases the availability of locally produced feed products (BSFL protein and oil), but also it reduces the dependency on the imported animal feed materials. Oil is an important feed component especially for piglets. Feeding oil to piglets reduces the mortality rate of piglets. However, based on our observations, the usage of oil in livestock feed (such as pig and piglet) is rare in Uganda while oil provides essential fatty acids which strengthen the immune system in piglets. Although, the cost of insect oil is higher compared with the crop oil, because of feed-food competition, and increasing demands for the soybeans from food industry, this will get more attention in near future. Moreover, based on the obtained results, the environmental benefit of the BSFL is higher than soybean and fish meal which is an important parameter for considering it as a good alternative for the typical animal feed components.

Although the present assessment was based on the data provided by an industrial BSFL unit, they need further laboratory tests to result in more accurate values. More accurate data on the nutritional value of produced larvae and organic wastes used for feeding larvae leads to more precise evaluation. The avoided emissions from landfill highly depend on the composition of organic wastes. Therefore, it should be considered in further calculations. Moreover, it is suggested to study the environmental impacts of the BSFLs rearing on different available organic wastes (fish residues, maize distillers, crop residues, etc.). The caried out studies showed a lower CF for brewer's grains and okara compared to maize distillers and hen diet (Bava *et al.*, 2019). Insect diet affects the growth performance and the chemical composition of larvae. Therefore, in addition to the environmental and economic aspects, it is crucial to consider insect diet to meet the market requirements. To monitor the larvae production unit better, it is suggested to conduct regularly tests to measure production factors such as growth rate (feed conversion efficiency, total larvae yield and individual larvae body weight), mortality rate, etc. These parameters directly affect the economic efficiency of production unit and indirectly on the environmental sustainability. However, as Smetana *et al.* (2016) and Bava *et al.* (2019) highlighted, a higher efficiency in term of the BSFL yield (and protein content) is usually achieved using the BSFL feed with high nutritional value (e.g., rye meal, soybean meal), which results in higher environmental impacts of produced BSFL. Therefore, it is important to determine the optimum level in which the production is maximum while the environmental impacts are minimum. In order to have a more holistic evaluation, it is suggested to consider other environmental impacts such as acidification, water use, etc. For example, dumping organic wastes in landfill might lead to other nutrient pollutions which needs to be studied.

To sum it up, as it has been shown, there is environmental benefits for the BSFL production in Uganda which needs to be considered. In terms of economic aspect, more work need to be done to reduce the costs of production to make the insect production more feasible. Due to the fact that developing such production unit requires more investment, a more external support is needed. Investments on insect production approaches and related projects to reduce the cost of production needs to be taken into account by the governments. Moreover, livestock producers need to be educated about the importance of larvae oil on health of livestock.

4 Conclusion

The BSFL production system can play an important role in circular economy and efficient use of resources in the world. In addition to its positive impact on economy, the impact of the BSFL production system needs to be assessed. Therefore, this study aimed to assess both positive and negative environmental impacts of rearing BSFLs. Both the produced and avoided GHG emissions determined for a production process of BSFL in a production unit in Uganda. Based on the obtained results the CF of produced larvae was 3.1 kg CO_2eq per kg dried larvae which was equal to 8.16 kg CO_2eq per kg protein. Energy and transport were the main contributors to total GHG emissions. The avoided emissions of BSFL product were determined by determining the environmental impacts of dumping organic wastes in the landfills, the CF of chemical fertilizers and the CF of commonly used feed components (soybean meal and fishmeal). For the last item, the most commonly used feed components which can be replaced by BSFL products were identified, their carbon footprint was calculated, and the replacement ratio determined. Our results showed that production of 1 kg dried larvae from organic wastes avoids around 5.2 kg CO_2eq. The main source of avoided emissions was replacing commonly used animal feed components with the larvae products. Using organic waste in the production process instead of dumping in the landfills and using the BSF manure as an organic fertilizer were the other sources of avoided emissions in the BSFL production system.

Based on the results of this study it can be concluded that replacing animal feed components such as soybean meal and fishmeal by the BSFL products, reduces the environmental impacts of pig, poultry and fish production systems. Despite the high potential of the BSFL to reduce the environmental impacts of food products, some actions such as increasing the efficiency of rearing process needs to be considered to reduce the total GHG emissions of the BSFL production system.

In addition to the GHG benefits for production of BSFL, its land and water requirement is low. Moreover, it has a high contribution to the circular economy by converting organic waste into high-quality feed ingredients. Improving the livelihood by increasing the employment is an important benefit of BSFL production in East Africa. Replacing the commonly used animal feed ingredient with the BSFLs increases the availability of soybean, maize that can feed people in East Africa. Therefore, a more extensive study helps to highlight the greater positive impacts of BSFLs.

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