



Black Soldier Fly biowaste treatment – Assessment of global warming potential



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ABSTRACT

Cities of low and middle-income countries face severe challenges in managing the increasing amount of waste produced, especially the organic fraction. Black Soldier Fly (BSF) biowaste treatment is an attractive treatment option as it offers a solution for waste management while also providing a protein source to help alleviate the rising global demand for animal feed. However, to-date very little information is available on how this technology performs with regard to direct greenhouse gas (GHG) emissions and global warming potential (GWP).

This paper presents a study that uses a life cycle assessment (LCA) approach to assess the GWP of a BSF waste treatment facility in the case of Indonesia and compares it with respective values for an open wind-row composting facility. Direct CH₄ and N₂O samples were extracted from BSF treatment units and analyzed by gas chromatography. Results show that direct CO₂eq emissions are 47 times lower the emissions from composting. Regarding the overall GWP, the LCA shows that composting has double the GWP of BSF treatment facility based on the functional unit of 1 ton of biowaste (wet weight). The main GWP contribution from a BSF facility are from: (1) residue post-composting (69%) and (2) electricity needs and source (up to 55%). Fishmeal production substitution by BSF larvae meal can reduce significantly the GWP (up to 30%). Based on this study, we conclude that BSF biowaste treatment offers an environmentally relevant alternative with very low direct GHG emissions and potentially high GWP reduction. Further research should improve residue post-treatment.

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1. Introduction

Cities of low and middle-income countries face tremendous challenges with providing adequate solid waste management (SWM) services to ensure public health and avoid pollution to the environment. Besides rapid urbanization and population growth, limited skilled human resources, unreliable and lacking financial resources, ineffective institutional arrangements and inappropriate technical infrastructure exacerbate the challenge (Guerrero et al., 2013; Scheinberg et al., 2015; Wilson, 2015). In low and middle-income settings, SWM systems are still characterized by low collection rates and inadequate waste disposal: collection rates range between 30 and 80% and of the collected waste often well less than 50% is disposed of in controlled disposal site, and uncontrolled disposal is still quite common in rural areas in many countries (Scheinberg et al., 2015). Uncontrolled disposal may result in the release of methane into the environment – a potent greenhouse

gas (GHG). Methane from landfills and wastewater account for ~90% of all global waste sector emissions, or about 18% of the global anthropogenic methane emissions (Bogner et al., 2008). This is especially relevant as one of the main characteristics of municipal solid waste generated in low and middle-income settings is its high fraction of organic waste, also called biowaste, comprising food and kitchen waste (e.g. from households, restaurants, hotels, schools, hospitals), market waste, yard and park waste, and residues from food and wood processing industries (Hoornweg and Bhada-Tata, 2012). In low and middle-income settings, biowaste reaches around 50–70% of the total waste produced, contrasting the 20–40% obtained in high-income settings (Wilson, 2015). Therefore, if the disposal of biowaste can be decreased by diversion and treatment with lower emissions measures (e.g. composting or other organic waste treatment options) it is possible to reduce considerably the amount of methane emissions.

Under the global warming and climate change debate, addressing the issues of biowaste treatment, and implementing treatment alternatives to disposal, has gained the interest of national and municipal decision-makers as well as researchers worldwide

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(Salomone et al., 2017; Sandec, 2008; Wilson, 2015). Besides the benefits of diversion from landfills, biowaste treatment and valorisation also stimulates waste collection through the creation of a product with economic value (Iacovidou et al., 2017a; Iacovidou et al., 2017b), thus returning resources to the economy using a circular approach – an important feature of sustainable development (Millward-Hopkins et al., 2018). Biowaste treatment and valorisation options can be classified according to the use of the end-products generated. These can be end-products such as fertilizer or soil amendment, energy and fuel or protein for animal feed. A comprehensive overview of potential recycling pathways for biowaste are shown in more detail in Lohri et al. (2017). From this variety of option, this paper focuses on one of the more innovative biowaste treatment options, where waste is fed to insect larvae – in this case the larvae of the Black Soldier Fly (BSF) – and when harvested are used as animal feed. The availability of conventional animal feed, such as soymeal or fishmeal, is increasingly limited and expensive, or associated with high land and water needs (Makkar et al., 2014; Smetana et al., 2016). Using biowaste as substrate for insect rearing as protein source in animal feed is therefore considered a very promising alternative (Salomone et al., 2017).

After its first introduction for waste treatment back in the 1990s, Black Soldier Fly (BSF), *Hermetia illucens*, is gaining more and more interest (Makkar et al., 2014; Smetana et al., 2016; Surendra et al., 2016) as an efficient way to convert biowaste into protein-rich and fat-rich biomass suitable for animal feeding. The approach is to feed fly larvae with biowaste. This reduces the waste amount by 50–80% (wet weight) to a residue and can grow larvae that can be harvested after about 14 days with a waste-to-biomass conversion rate of up to 20% (on a total solid basis) (Lohri et al., 2017). Larvae can be further processed and used as substitute for fishmeal in conventional animal feed (Henry et al., 2015) and residue can be composted and used as soil amendment (Diener et al., 2009).

Given the continuing efforts of nations and local governments towards reducing GHG emissions, and the commitments taken by all states that are parties to the United Nations Framework Convention on Climate Change, decision-makers increasingly evaluate the Global Warming Potential (GWP) of different treatment options when choosing biowaste management approaches (Wilson, 2015). For the more conventional approaches such as composting or anaerobic digestion this information is well established and simplified methodologies are available under the Clean Development Mechanism (CDM) framework. However for innovative technologies, such as BSF waste treatment that is still in an early stage of research (Lohri et al., 2017), to-date such information is scarce. Previous studies using a LCA approach for assessing the GWP of BSF exist, but typically used literature data from other insects to evaluate the potential direct GHG emissions, and focus either on a comparison of feed from BSF versus production of other feed (Smetana et al., 2016) or biowaste conversion using reference data from high-income countries (Komakech et al., 2015; Salomone et al., 2017). The main objective of the present study was therefore to fill this research gap by: (1) evaluating the direct GHG emissions from the BSF treatment process in terms of methane (CH₄) and nitrous oxide (N₂O) emissions and production pathways, (2) using a life cycle approach to assess the GWP of an Indonesian BSF treatment facility, and (3) comparing this to theoretical calculations of GWP using data from an Indonesian composting facility.

2. Methods

2.1. Direct GHG emissions

2.1.1. BSF treatment process

To evaluate CH₄ and N₂O emissions and production pathways from the BSF treatment process, a sampling campaign was

conducted at the BSF treatment facility of Puspa Agro (7°22'10.7"S, 112°41'05.4"E) in Sidoarjo, Indonesia in June 2016. CO₂ production was also measured to check its accumulation and to detect leakages.

At Puspa Agro BSF facility, source segregated kitchen waste is treated by BSF larvae. The treatment process takes place in plastic boxes of 40 × 60 × 15 cm and lasts for 13 days. On day one, boxes are each filled with 10,000 5-day old larvae and 5 kg of kitchen waste (23% TS). Subsequently, on day five and eight, another 5 kg of kitchen waste is added to the boxes, thus obtaining an overall treatment capacity of 15 kg per box. These procedures follow the recommendations of Dortmans et al. (2017).

Direct CH₄ and N₂O emissions and production pathways in a BSF treatment process treating 1 ton of biowaste were assessed by a gas sampling campaign conducted at this BSF treatment facility. During the sampling campaign, the kitchen waste fed to the larvae consisted mainly of fruit and vegetable raw peeling as well as cooked food remain such as rice and vegetables. Through a rough calculation, a carbon-to-nitrogen ratio (C/N) of 15–20 was estimated. Households segregated the kitchen waste, which was then collected daily by a separate collection vehicle and delivered directly to the facility.

Gas sampling was done every day in triplicates. To ensure even distribution of gases within the box, a small battery driven fan was inserted into three boxes with larvae and kitchen waste. Each box was covered with a second plastic box (40 × 60 × 10 cm) equipped with a valve outlet. The two boxes were hermetically sealed and left untouched following the static chamber principle (Chan et al., 2011; Nigussie et al., 2017). From the air inside each sealed box, a predefined volume of gas was sampled in duplicate after 90 min. On every second day, an additional duplicate sample was extracted 45 min after sealing. For the extraction of the sample, a 100 ml gas-tight syringe was used. The gas from the syringe was then injected into 120 ml glass vial pre-filled with argon (Ar). Pre-filled vials with Ar were used to ensure pure gas sample for stable storage and transport conditions. For filling each vial, five consecutive extractions from the boxes and injections into the vials were conducted. To avoid over-pressure in the vial, Ar was left to exit through an inlet-outlet valve system.

This sampling process was conducted daily from the same three defined boxes always at the same time of the day. The schedule of sampling was established based on the assumption that a maximum GHG production rate is most likely observed around 1–2 h after adding fresh feedstock to the box. Ambient air samples were also taken every second day. All vials were transported by plane to Switzerland, where they were analyzed within a month using a gas chromatograph (GC) configured for CH₄, CO₂ and N₂O¹. The residual Ar concentration was assessed using the *miniRuedi* portable mass spectrometric system (Brennwald et al., 2016), which resulted in a gas dilution factor of 4%.

The overall gas production was calculated as follows: firstly, we subtracted the ambient gas concentration from the box's gas sample concentrations using the GHG concentrations obtained with the GC device expressed in ppm by volume. Secondly, we calculated the amount of GHG obtained in the boxes following the ideal gas law. Thirdly, we evaluated daily gas production rates based on the 45 and 90 min measurements. Results showed that 45 min after closure of the boxes, on average 55% of CO₂ was emitted, so a linear production rate over time can be assumed. However, for N₂O and CH₄ emission rates after 45 min were 77% and 86% of the total. Therefore, closing of the boxes has an impact on BSF larvae behavior and feeding which results in lower emissions in the

¹ CH₄ and CO₂: Carbonplot 30 m × 0.53 mm × 30 micron (Ref Supelco 25467), FID (370 °C); N₂O: Carbonplot 30 m × 0.32 mm × 3 µm (Ref Agilent 113-3133), ECD (50 °C).

second half of closure period. We used the 45 min measurements and assumed this rate as constant gas flux between two consecutive samplings.

The potential GHG production pathways were assessed analyzing the daily average CH_4 and N_2O concentrations and reviewing related scientific literature.

2.1.2. Residue post-composting process

To assess gas production by residue post-composting, we used the default values defined for Clean Development Mechanism (CDM) projects (UNFCCC, 2011). Lacking real measured data, these estimates were assumed to best describe the direct GHG emissions from low-tech composting facilities found in low- and middle-income settings.

2.2. Life cycle assessment

To assess the GWP of BSF treatment and compare it with composting treatment, a LCA with SimaPro8 software was performed using Ecoinvent 3.1 database for background data. Energy consumption of BSF treatment relied on the facility in Sidoarjo whereas for composting data from the TEMESI composting facility in Bali (Temesi, 2016) was utilized. The standardized LCA (ISO, 2006) was followed and is detailed hereafter. The recommendations given by Laurent et al. (2014) when performing a LCA on SWM issues were also considered.

2.2.1. Goal, scope and functional unit

The goal of the study was to conduct a LCA of BSF treatment and compare the GWP of treating 1 ton of biowaste with the GWP from composting. Therefore, the functional unit (FU) was to effectively treat 1 ton (wet weight) of biowaste and produce compost. The focus was on treatment options in Indonesia and aims at providing a first qualitative and quantitative GWP assessment of BSF treatment in low and middle-income settings as well as comparing these to composting.

2.2.2. System boundaries

The system boundaries used in the study are shown in Fig. 1 and Fig. 2. The systems, as analyzed, start with segregated household biowaste entering the treatment facility and end with compost production.

All aspects of waste generation, collection and transport were ignored as they are not expected to differ between the two treatment technologies. Also, compost transportation to customers and subsequent use with its respective impacts was not considered in the LCA. Given the low market demand in Indonesia for soil improver or fertilizer (Verstappen et al., 2016), compost was assumed to be used as landfill cover whereby neither negative (leachability) nor positive impacts (methane oxidation) (Laurent et al., 2014) were taken into account.

To consider the added value of produced larvae meal, the substitution method (JRC-IES, 2010) was used. We assumed that the produced larvae meal substitutes conventional Peruvian fishmeal (production and transport), using available statistical data from

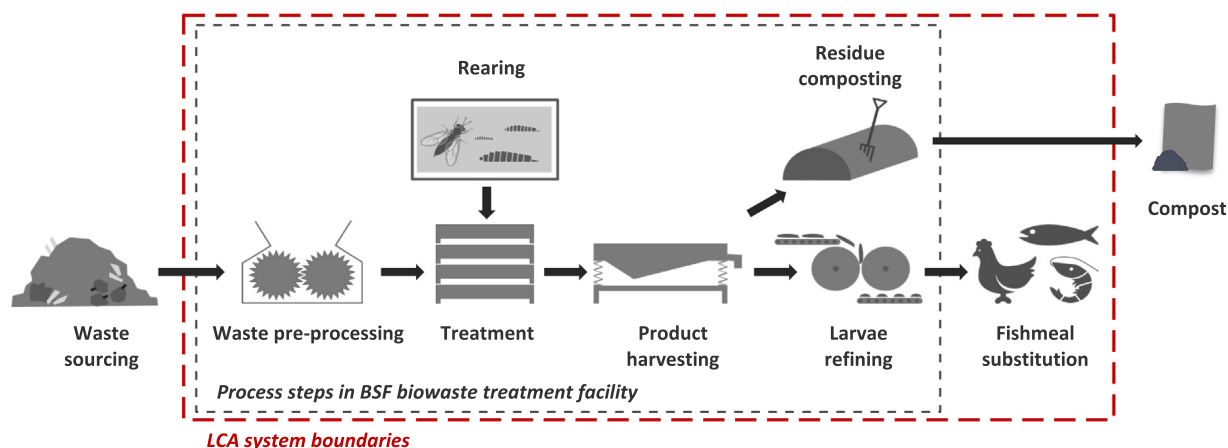


Fig. 1. Schematic diagram of the BSF treatment system considered.

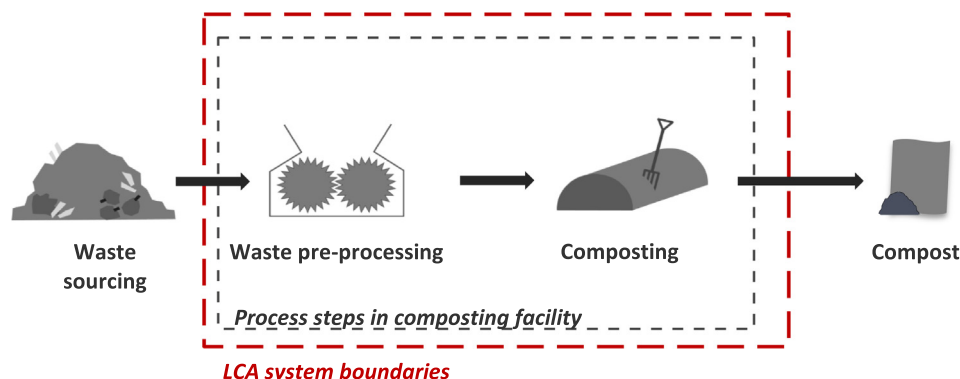


Fig. 2. Schematic diagram of the composting system considered.

Indonesia regarding fishmeal imports. In a second scenario we also considered only the substitution of locally produced Indonesian fishmeal. Potential benefits from BSF-derived oil were not considered in the present study as limited primary data is available (Surendra et al., 2016).

The indirect emissions related to infrastructure, equipment and machinery were neglected. The study of Salomone et al. (2017) shows little influence of the BSF facility equipment on GWP. As both treatment approaches (BSF and composting) use a similar level of infrastructure and machinery we hypothesize that this impact can be neglected.

Direct CO₂ emissions from biowaste during the treatment processes were regarded as biogenic and not considered in the inventory analysis due to the scope of the current LCA study (Christensen et al., 2009).

2.2.3. Life cycle Inventory (LCI)

All systems analyzed are briefly described below and the assumptions with relevant references are summarized in Table 1

and Table 2. For background data such as electricity, water and energy supply, Ecoinvent database 3.1 was used.

2.2.3.1. Black Soldier Fly treatment. Energy and water consumption for the different processes was assessed directly at the BSF treatment facility of Sidoarjo, adapted to a treatment capacity of 1 ton of household biowaste per day. Detailed explanations on the treatment processes can be found in Dortmans et al. (2017).

Rearing. Rearing of the flies takes place in the nursery and is distinctly separated from the waste treatment process. The rearing process consists of 4 phases: (1) fly mating and egg laying phase in cages, (2) egg hatching phase and growth of larvae until 5 day old larvae (5-DOL) – where at the end of this phase a large part of 5-DOL are moved from the rearing section to the waste treatment process, (3) the larvae remaining in the rearing section are then fed further until their prepupae stage, and finally (4) a pupation and fly emerging phase in dark cages.

Most of the electricity consumption in the rearing process is used for ventilation and lighting. Ventilation is required to ensure

Table 1
Life Cycle Inventory data for the BSF treatment facility.

| BSF treatment facility | BSF treatment facility of Sidoarjo in use in June 2016 | | |
|--|---|--|---|
| | Assumptions for 1 ton/day | Details | Source |
| Rearing | Ventilation: 1.76 kWh Lighting: 1.10 kWh Mixing: 0.02 kWh Compost: 3.57 kg Chicken feed: 3.1 kg | 2 ventilators 220 W; 12 h/day for 3 tons 1 lamp 300 W; 5 h/day for 3 tons 12 lights 25 W; 6 h/day for 3 tons 1 mixer 5500 W; 5 min/week for 21 tons 75 kg/week for 21 tons 1.8 mg/larvae from hatching to 5-DOL 240 mg/larvae from hatching to prepupae 25 l/week for 21 tons | Sidoarjo Zeist et al. (2012) |
| Waste pre-processing | Water: 1.19 l Manually done No electricity consumption | No shredder use | Sidoarjo |
| Treatment | Natural air flow simulation No electricity consumption CH ₄ : 0.4 g N ₂ O: 8.6 g | Direct emissions Direct emissions | Sampling campaign |
| Product harvesting | Pressurized water: 2.93 kWh Water: 664 l | 2.2 kW; 80 min/day 8.3 l/min; 80 min/day | Sidoarjo |
| Larvae processing | Boiling: 3 kg LPG Sun drying | 1.5 LPG/day for 0.5 ton | Sidoarjo |
| Residue composting | Electricity: 0.56 kWh Diesel: 0.22 kg CH ₄ : 630 g N ₂ O: 63.3 g | Direct emissions Direct emissions | Temesi (2016), UNFCC (2011) |
| Cleaning | Cleaning: 1.46 kWh Washmachine: 0.96 kWh Water: 381 l | Cleaning: 2.2 kWh; 40 min/day Washmachine: 350 kWh/365 use; 1 use/day Cleaning: 8.3 l/min; 40 min/day Washmachine: 49 L/wash | Sidoarjo |
| Avoided emissions Fishmeal production | 100% fishmeal substitution Peruvian fishery Diesel: 2.08 kg Light fuel oil: 1.98 kg Electricity: 8.178 MJ | Peruvian fishmeal production | Zeist et al. (2012) |
| Transport | Cargo: 1047 tkm Lorry: 1.873 tkm | Boat from Callao-Surabaya Lorry from Surabaya Sidoarjo | SeaRates (2005–2017) |

Table 2
Life Cycle Inventory data for the composting facility.

| Composting facility | Yayasan Pemilahan Sampah Temesi Facility Bali – Annual electricity and diesel consumption | | |
|----------------------|--|--|---------------|
| | Assumptions | Details | Source |
| Waste pre-processing | No electricity consumption | Manual (no shredder used) | Temesi (2016) |
| Composting | Electricity: 1.77 kWh Diesel: 0.7 kg CH ₄ : 2000 g N ₂ O: 200 g | Forced aeration + Sieve Excavator Direct emissions composting Direct emissions composting | |

fresh air circulation inside the rearing room. Electric lights are used to attract emerged flies from the dark cages into the mating cages and to light the whole rearing room. Water, compost and an electric blender are necessary to prepare the attractant material placed in the mating cages. Chicken feed is used to feed larvae for the first 5 days and for larvae kept in the rearing facility until they reach their prepupae stage. The compiled data presented in Table 1 are derived from a larvae production facility treating 3 tons of bio-waste per day.

Pre-processing. Household biowaste arriving at the BSF treatment plant is already segregated and therefore free of inorganics, so no further sorting was required. Although for other biowaste types shredding may be required, in this particular case no shredder was used.

Treatment. Waste treatment takes place in plastic boxes piled on top of each other in stacks located in the treatment hall. The treatment process takes 13 days. A specified number of 5-DOL from the rearing facility are added to a certain amount of waste in each plastic box. The larvae consume the organic waste and grow. Each plastic box contains 10,000 larvae and 15 kg of biowaste is fed manually in three feeding events. Direct gas emissions from plastic boxes containing larvae and waste were sampled during the campaign conducted in Sidoarjo in June 2016 and analyzed for CH₄ and N₂O in fall 2016.

Product harvesting. After 13 days, larvae are manually separated from residue using a sieve. Hereby the mixture of larvae and residue is spread out onto the sieve, where then larvae crawl through sieve's holes to a recipient below to avoid sunlight. A pressurized water system is used to clean the recipient and flush larvae to a harvesting system.

Larvae processing. Harvested larvae are dipped into boiling water. Water is brought to boil with liquefied petroleum gas (LPG). Thereafter larvae are sun dried.

Residue composting. After larvae harvesting, the remaining residue is composted using the same approach as a typical biowaste composting process and as presented in Section 2.2.3.2. The emission values from composting were adjusted for treating 320 kg of residue (this represents the average amount after treatment of 1000 kg of incoming waste) following a linear extrapolation.

The emissions from composting of the residue were not measured directly, as explained in Section 2.1.2. Our assumption was that the residue shows similar emissions during composting as fresh biowaste composting. As the residue is partly degraded from the BSF digestion process, we expect less emissions as compared to fresh biowaste composting, thus our assumption may be overestimating the direct emissions of residue composting.

Additional processes. The facility requires regular cleaning of all equipment. Energy (washing machine and high pressure cleaner) and water consumption were hereby considered.

Fishmeal substitution. Harvested larvae were assumed to substitute current conventional Peruvian fishmeal by a ratio 2:1. This ratio is justified as fishmeal contains on average twice the protein content of larvae meal on a wet weight basis (adapted from Diener et al. (2009)).

Energy consumption in production process of fishmeal was based on the data provided by FeedPrint 2015.03 database (Zeist et al., 2012). Furthermore, transport by cargo ship from El Callao-Peru to Surabaya, Indonesia, and by lorry from Surabaya to Sidoarjo was also considered. The transport distances were used from SeaRates (2005–2017).

2.2.3.2. Composting. Composting facility of Yayasan Pemilahan Sampah Temesi – Bali (Temesi, 2016) was used as source of data for energy consumption during composting process. This compost-

ing facility operates as an open forced aeration composting system, with the capacity to treat 60 tons of biowaste per day. Based on the energy consumption at this capacity, the equivalent energy consumption at 1 ton of waste capacity was estimated using a linear extrapolation.

Waste handling. The handling of waste input is manual without consideration of machinery (no waste shredder is used).

Composting process. During composting blowers powered by electric fans ensured forced aeration. Composting heaps are also turned using a diesel fueled wheel loader. After 3–4 months of composting duration, compost product is sieved using an electrical powered compost sieve. The sieved product is then left to further mature for 1–2 months before it is sold (Zurbrugg et al., 2012).

Values for direct emissions of CH₄ and N₂O from composting are taken from UNFCC (2011) (default values of non-monitored data used).

2.2.4. Impact assessment and interpretation

The study presented here focuses on GHG emissions and GWP, calculated using IPCC 2013 100a method (IPCC, 2013).

ReCiPe Midpoint Hierarchist (H) methodology was also used to assess all impact categories. These results are not presented here. The impacts show high correlation with the Indonesian coal power plant electricity production.

A sensitivity analysis was carried out following the recommendations given by Clavreul et al. (2012) to evaluate which variables have a dominant influence on the overall results. A contribution analysis was conducted to show the critical processes in terms of kg CO₂eq emissions. Also a perturbation analysis was conducted to highlight the critical variables using the sensitivity ratio (SR) with an increase of 10% of each variable separately. Finally, also alternative scenarios were developed and analyzed. A combined sensitivity analysis was however not carried out as we considered only one main impact category.

3. Results and discussion

3.1. Direct GHG emissions

The results obtained from the three boxes confirmed the reliability of the method of emission measurement used. The three boxes showed similar process efficiency, with a biowaste reduction of 50% and larvae biomass growth of 20–25% (wet weight). An average variation of GHG emissions of 20–30% between boxes was observed. We considered this as an acceptable range of variation, considering it being a biological treatment process with non-homogeneous feedstock.

Results show an average CH₄ production of 0.4 g and N₂O production of 8.6 g per ton of organic household waste treated. The results were compared with GHG emissions from open composting as described in the literature (see Table 3). The wide range of composting GHG emissions mentioned in literature results from a large range of different feedstocks, and/or treatment parameters measured (Boldrin et al., 2009; Chan et al., 2011). In general, the assumption is however valid that lower technical complexity of the composting system results in higher direct GHG emissions. The default values defined by UNFCC (2011) for Clean Development Mechanism (CDM) projects thus represent the direct GHG

Table 3
CH₄ and N₂O direct emission production from BSF treatment and composting.

| | CH ₄ [g/ton ww] | N ₂ O [g/ton ww] | References |
|------------|----------------------------|-----------------------------|-----------------------|
| BSF | 0.4 | 8.6 | Present study |
| Composting | 30–6'800 | 7.5–252 | Boldrin et al. (2009) |
| | 2'000 | 200 | UNFCC (2011) |

emissions from low-tech composting facilities quite well. Such facilities would typically be found in Indonesia and other low- and middle-income settings.

The BSF direct emissions are also closely linked with feedstock characteristics and treatment parameters (ratio of larvae and amount of waste). The comparison of BSF treatment versus composting with regard to direct GHG emissions (Table 3) nevertheless highlights the potential of BSF treatment as a low GHG emissions option.

Besides evaluating how much GHG emissions the BSF biowaste treatment emits, this study also assessed the potential production pathways through an analysis of the daily production rates over the whole treatment period. When considering GHG production from BSF biological treatment process two pathways can be assumed: 1) metabolic GHG production from the larvae 2) waste decomposition itself enhanced or hindered by larvae's activity. The potential CH_4 and N_2O production pathways are detailed in Sections 3.1.1 and 3.1.2.

3.1.1. CH_4 production pathways

Fig. 3 shows that over the whole treatment period, CH_4 concentrations were low (1.4 to 2.7 ppm on average) and similar to the

one observed in air samples. No pattern can be detected. This indicates that metabolic CH_4 production from the larvae is low or absent and that larvae movement and related aeration of the waste hinders anaerobic conditions. This finding goes in line with the study of Hackstein and Stumm (1994) and Čičková et al. (2015) showing no methanogenic bacteria present in the hindgut of House Fly larvae and stating that fly larvae's main contribution on biodegradation seems to be the mechanical aeration. This was also confirmed more recently with the study of Perednia et al. (2017) that state that BSF larvae grown under aerobic condition do not generate significant quantities of CH_4 .

3.1.2. N_2O production pathways

As can be seen in Fig. 4, the N_2O concentrations in the treatment boxes do not differ significantly from the ambient air sample (0.3 ppm), except after the two feeding event (day 5 and 8). The increase on day 5 and 8 is proportional to larvae weight, which indicates an impact of larvae activity on N_2O production.

To the knowledge of the authors, even though direct N_2O emissions from insects have been studied before (Oonincx et al., 2010), none of these focused on BSF larvae specifically. According to the

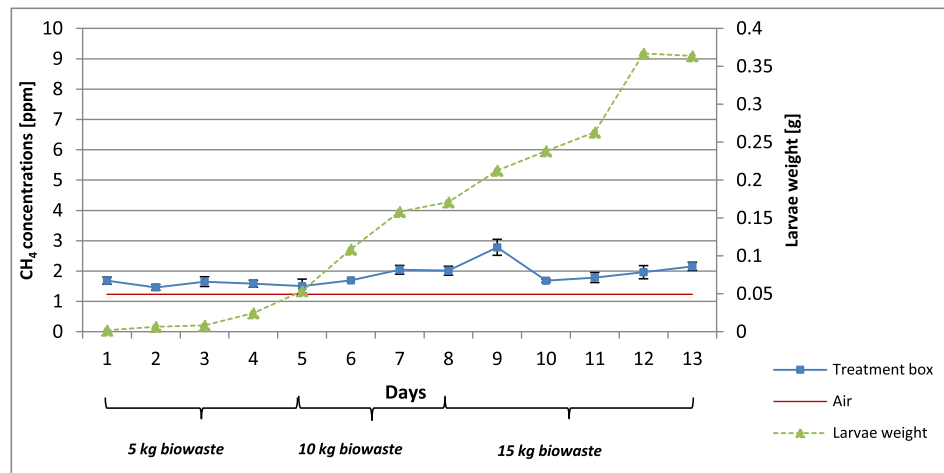


Fig. 3. Daily average direct CH_4 emission concentrations in BSF treatment boxes (solid line with square) and related standard deviation (error bars) observed after a 90 min closing time, as well as average CH_4 concentrations in air (solid line) expressed in ppm in correlation with larvae size expressed in g of average wet weight per larvae (dashed line with triangle).

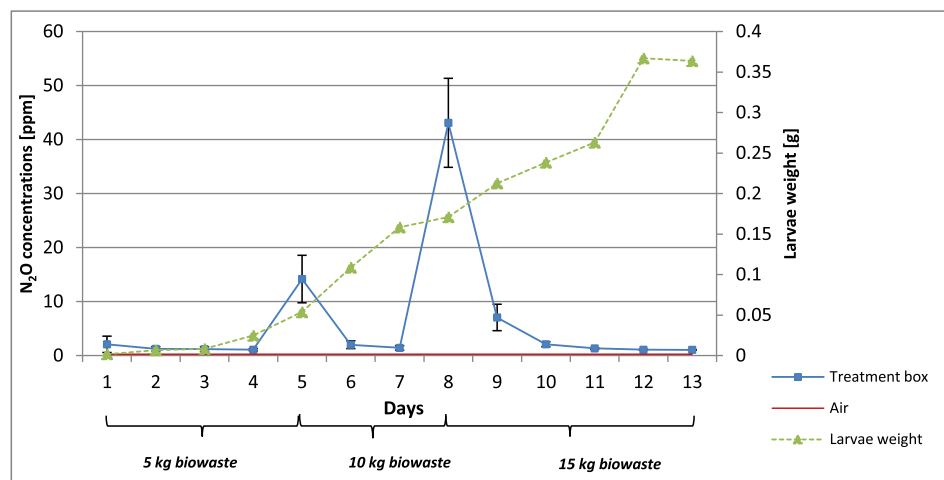


Fig. 4. Daily average direct N_2O emission concentrations in BSF treatment boxes (solid line with square) and related standard deviation (error bars) observed after a 90 min closing time, as well as average N_2O concentrations in air (solid line) expressed in ppm in correlation with larvae size expressed in g of average wet weight per larvae (dashed line with triangle).

study of Iwasa et al. (2015) on GHG emissions from fly larvae on cattle dung, metabolic N_2O emissions from fly larvae are unlikely as the presence of fly larvae show lower overall N_2O emissions when compared to cattle dung decomposition without larvae. Based on the results of our study it is not possible to distinguish between metabolic or bacterial N_2O production. We estimated that mechanical aeration occurring in the waste could be responsible of general low N_2O emissions.

The complexity of evaluating the impact of saprophages on N_2O emissions was already highlighted by the study of Nigussie et al. (2017) on earthworms and garden waste decomposition. Results of Nigussie et al. (2017) showed that a high feeding rate increases N_2O emissions. This is also seen in our results, where after a feeding event, N_2O increases.

3.2. Global warming potential assessment

Based on the considered systems and assumptions, the overall GWP per ton of biowaste is 35 kg CO_2eq for BSF treatment and 111 kg CO_2eq for composting (Fig. 5).

3.2.1. Direct emissions

Direct emissions from a BSF treatment facility (i.e. BSF treatment itself and residue composting) are lower than from a composting facility. For BSF treatment they represent 72% of the overall related GWP while for composting they represent 98%. The calculation of the sensitivity ratio (SR) shows that N_2O direct emissions is the most critical parameter with a SR of 278 for the emissions from biowaste composting, 88 for residue composting and 12 for the BSF treatment process. CH_4 direct emissions is the second most important parameter, having a SR of 30 and 9.5 for the emissions from biowaste composting and residue composting respectively. This highlights the importance of optimizing the biological processes for ensuring low GHG emissions. All other SR values are below 0.3.

In the BSF system considered, the direct emissions from residue composting is responsible for 68% of the total GWP of BSF treatment. These high values are a consequence of the default value used, regarding emissions from composting according to UNFCCC (2011) and our conservative assumption that emissions from residue composting are the same as those when composting fresh biowaste. Boldrin et al. (2009) present a wide range of values for open

composting emissions. Compared to the default value of UNFCCC (2011) these range from 3 to 235% of the default value and are explained by the wide range of operational parameters that influences emissions, such as system design, aeration rate, turning frequency, and/or feedstock used. Based on these literature values, it is likely that we overestimate emission from residue composting especially considering the composition of the “feedstock”. Residue after BSF treatment is lower in nutrients and carbon (as these have been consumed by the larvae) when compared to fresh biowaste. The resulting emissions based on feedstock characteristics would therefore also go towards the lower end of the values given by Boldrin et al. (2009). To confirm this, a detailed analysis on residue composition and carbon and nitrogen mass balance would be necessary. This was unfortunately not achievable in this study due to technical on-site limitations and lack of secondary data. Therefore, we feel the use of the default value from CDM is justifiable and allows an approximation. Even if residue composting emissions are overestimated the results presented in Fig. 5 nevertheless emphasize the importance of residue post-treatment options.

3.2.2. Indirect emissions

When considering the indirect emissions, it is the electricity consumption for BSF treatment that plays a major role. We considered a direct electricity consumption of 8 kWh for BSF treatment and 1.8 kWh for composting. This contributes to 19% of the overall GWP of BSF treatment and 2% for composting. The rearing and harvesting phases in BSF treatment are those consuming most of the electricity needs in the current BSF system and scale (around 35% each). The sensitivity ratio obtained for electricity consumption (0.22) shows that a slight reduction of electricity consumption with the current system will not considerably affect the overall GWP. However, introducing new processing steps and equipment such as a shredder for the feedstock, active ventilation systems or a shaking sieve for larvae harvesting, could increase electricity consumption significantly. With such equipment we estimated that the electricity consumption could amount to 35 kWh per ton of waste treated. This would increase the overall GWP by a factor of 1.8. However, this factor is strongly influenced by the energy source. In the system presented, we used the Ecoinvent 3.1 data on Indonesian electricity supply at grid coming from coal power facilities. The associated GWP per kWh consumed is therefore high (1.17 kg CO_2eq/kWh) in comparison with the average

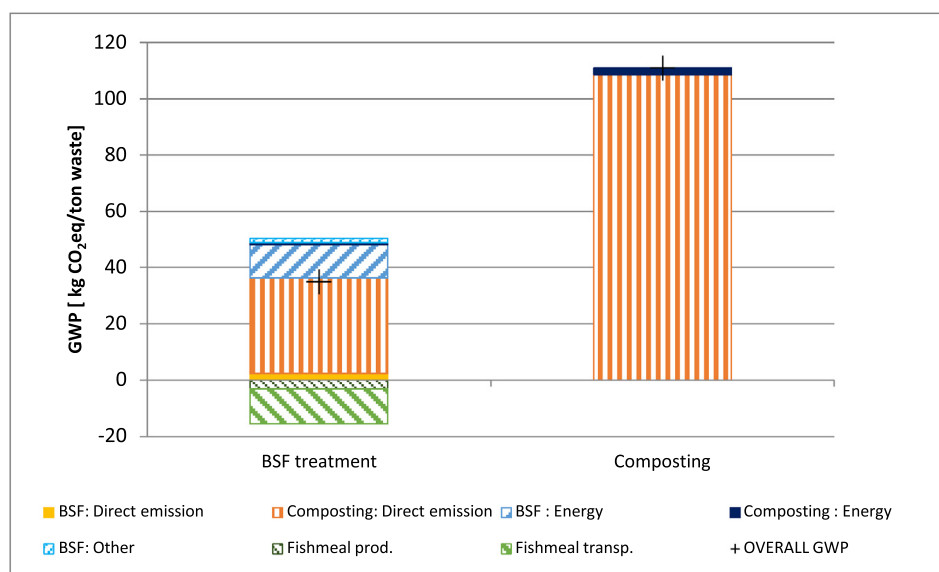


Fig. 5. GWP per ton biowaste (ww) expressed in kg CO_2eq from direct, indirect and avoided emissions of BSF treatment and composting.

non-European electricity production (0.72 kg CO₂ eq/kWh) or photovoltaic electricity production (0.07 kg CO₂ eq/kWh). When considering a 35 kWh/ton of electricity consumption, this would reduce the GWP from the electricity consumption and the overall GWP by 17 to 48%. Increasing the scale of operation will also affect the electricity consumption. With larger scale we expect more automation and an increase in power consumption, although economies of scale could also reduce the unit consumption per ton. As data on BSF treatment at different scales is not yet accessible, this could not be taken into account.

3.2.3. Avoided emissions

Avoided emissions from fishmeal substitution can amount to 31% when considering a 100% substitution of fishmeal produced in Peru and transported to Sidoarjo (Fig. 5). The major avoidance relates to avoiding cargo transport from Peru to Indonesia (25% of the total GWP avoided). Under the assumption that BSF larvae would substitute a locally produced fishmeal, this would only impact by 0–6% on avoided emissions, depending on the level of mechanization of the fishmeal production process. It is important to note that the larvae meal quality and its effect on how much fishmeal can be substituted was not considered in the scope of the present study.

In the analyzed system, the potential avoided emissions from compost transport and use were neglected. Residue composting in BSF generates half of the amount of compost as compared to fresh biowaste composting. When considering the fertilizer substitution value, Salomone et al. (2017) in their LCA showed that accounting for nitrogen fertilizer replacement could allow a significant negative contribution to GWP (−456 kg CO₂ eq/ton of waste treated). The higher compost product amounts would therefore favour the fertilizer substitution benefits from composting as compared to BSF treatment. However these estimated benefits depend on composition which relates to feedstock characteristics and on regional climate, soil and crop parameters (Laurent et al., 2014). Therefore the current information available does not allow a reliable estimate. This highlights the importance of further investigating the residue composition, possible post-treatment options and related end-product market demand when analyzing the overall GWP.

4. Conclusion and outlook

The main findings of this study show that: (1) when considering direct GHG emissions, BSF treatment shows lower emissions when compared to composting, (2) results from the LCA show that the overall GWP for BSF treatment mainly depends on the type of residue post-processing and the electricity consumption and energy source used, (3) More data on larvae meal quality are still required to better assess the potential of substitution of fishmeal and respective emission savings.

GHG emissions by the larvae feeding on the waste is very low, when compared to the microbial emissions in the open composting process. This can be explained given that the larvae continuously move the waste when feeding and thus ensure aeration and aerobic conditions. Unfortunately, we observed an influence of our experimental setup on the behavior of the larvae where sealing the boxes started to impact on larvae's behavior after at least 45 min. Thus, further experiments should be conducted using a continuous flow chamber sampling method.

Electricity consumption in the BSF treatment facility is a crucial element when considering overall GWP. With increased mechanization, electricity consumption per ton of waste will increase (shredder, mechanical sieve, etc.). Also, maintaining stable environmental conditions in indoor systems will significantly increase

electricity requirements thus increasing GWP. In low and middle-income settings where electricity production is based on fossil fuel origin, this accounts for high GWP. Here reducing and optimizing the electricity need is therefore of crucial interest. Our results show that consideration of renewable energy source such as solar panels is an eligible option as it could decrease the environmental impact associated with local electricity consumption.

Composting of the residue shows relatively high level of emissions given the default assumptions related to composting emissions. On one hand, better values about material-specific composting emissions would be helpful for more detailed assessments, while on the other hand further research on the characteristics of residues and best practice alternatives on how to process these residues considering emissions and end-product markets value is required. Among the post-treatment options, anaerobic digestion looks promising as it could tackle two problems at the same time: the residue management and the provision of an energy source to operate the facility. A recent study conducted by Lalander et al. (2018) shows promising results on biogas potential of BSF residue from food waste from a Swedish campus canteen (417 NmL g VS^{−1}). Further research is therefore needed to evaluate the biomethane potential of the household residue.

Finally, evaluating and quantifying avoided emissions from BSF biowaste treatment depends on emissions of the products which are substituted and how well the products from BSF-treatment are requested and accepted in the market. In our study, we considered larvae meal as an ideal substitute of conventionally produced fishmeal. Yet we know waste characteristics fed to the larvae influence larvae yield as well as larvae protein content (Smetana et al., 2016) and other quality parameters of the larvae meal obtained. Further research on suitable BSF diets, operational effects on product quality and impacts of feeding BSF larvae meal on farmed animals are necessary.

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