A comparison in product-value potential in four treatment strategies for food waste and faeces – assessing composting, fly larvae composting and anaerobic digestion

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Abstract

Municipalities are expected to provide solid waste management, which is funded by tax revenue or/and waste treatment fees. In many low- and middle-income countries, municipalities struggle to provide an adequate level of service, and in these places, the informal sector plays a major role in the collection and treatment of solid waste. In contrast to the plastic and metal fraction, the organic fraction is not managed by the informal sector, primarily because it has low or no financial value and treatment would cost more than the possible revenue. If the organic fraction could be converted to valuable products, the treatment could bear its own cost and this could act as an incentive to collect and treat this fraction. In this study, the potential product value generated through four treatment strategies treating food waste and faeces was compared in a Swedish context: (i) thermophilic composting; (ii) black soldier fly treatment (BSF treatment); (iii) anaerobic digestion (AD); and (iv) BSF treatment followed by AD (BSF + AD). In order to assess the AD strategies, the biomethane potentials of the substrates were assessed. Food waste had the highest biomethane potential, while BSF-treated faeces had the lowest (417 and 188 NmL g VS\(^{-1}\), respectively). Thermophilic composting yielded the lowest value product (organic fertilizer; 26 € t\(^{-1}\) treated food waste) and BSF treatment + AD the highest total value of products (animal feed, vehicle gas and organic fertilizer; 215 € t\(^{-1}\) treated food waste). The treatment costs were not taken into account here; the total value gives an indication of the cost margin for the different strategies studied. In places with an existing AD plant, BSF treatment + AD strategy is the most economically viable. In places where no such plant exists, BSF treatment is likely to be the most economically favourable treatment.

Keywords: animal feed, biogas, biomethane potential, economic assessment, Hermetia illucens, organic fertilizer

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Introduction

Treatment of solid waste is a service provided by municipalities, funded by tax revenue or/and additional waste treatment fees (Hoornweg & Bhada-Tata, 2012). In many places, however, governments and municipalities struggle to provide their citizens with adequate waste management, and in some places, this service is provided to less than 50% of citizens, despite being the single greatest budget item (Memon, 2010). Increased population growth and urbanization, along with increased consumption by the population, coupled with lack of resources, nonfunctioning treatment plants, lack of management skills, and unclear regulations and division of responsibility on the government side, contribute to the inadequate or lacking waste management services in low-income countries (Ngoc & Schnitzer, 2009). One major fraction of solid waste is made up of organic material. In high-income countries, this fraction is around 30% of the total amount of waste generated, while in low-income countries, it is around 60% (Hoornweg & Bhada-Tata, 2012). In low-income countries, organic waste can be given to animals as feed: for example, Katongole et al. (2011) reported that nearly half of all urban animal farmers in Kampala, Uganda, had at some time given market waste to their animals; nonetheless, Komakech et al. (2014) demonstrated that almost 90% of municipal solid waste reaching the landfill in Kampala was of organic origin. One reason for the percentage of organic matter being so high in many low- and middle-income countries is that the more valuable fractions (metal, plastic) are removed before land-filling by an informal sector comprising waste buyers, street waste pickers, municipal waste collection crews and dump/landfill waste pickers (Wilson et al., 2006). It is difficult to assess the role of this informal sector in waste recycling, but estimates suggest that it may...
handle 45% or more of the total waste generated and up to 70% of glass and metal waste (Linzner & Lange, 2013). Organic matter is not one of the fractions handled by the informal sector, and the reason is simply that no one would pay for it, as the cost of treatment is higher than the possible revenue from selling the products (Hogg et al., 2003; Lohri et al., 2017). Therefore, unless there are political, legislative or environmental incentives to treat organic waste, it is unlikely that a municipality struggling to provide waste management services to its citizens would invest in costly organic waste treatment technologies.

For a well-functioning waste management service to be provided to a greater number of people, it has been suggested that involvement of the private sector could be beneficial (Lohri et al., 2014). In affluent communities, entrepreneurs can build an organic waste management business based on subsidies and/or waste collection fees. In places where only low, or no, subsidies are provided for the organic waste management and the communities have a low purchasing power, some additional revenues may have be made to keep the organic waste management business economically viable.

One novel way of valorizing organic waste is by fly larvae composting, in which organic waste is converted into larval biomass and compost (Cicková et al., 2015). The larval biomass can be used as a protein source in animal feed, while the compost can be used as an organic fertilizer (Kroeckel et al., 2012; Lalander et al., 2015).

Another way of valorizing organic waste is by anaerobic digestion, in which biomethane is generated. The biomethane can be upgraded to vehicle-grade gas, converted to electricity in a gas turbine or used as a starting material in the synthesis of chemicals (Awe et al., 2017).

The aim of this study was to perform an economic assessment of four treatment scenarios for treatment of food waste and faeces: (i) thermophilic composting; (ii) black soldier fly larvae treatment (BSF treatment); (iii) anaerobic digestion (AD); and (iv) BSF treatment followed by anaerobic digestion (BSF + AD). In order to evaluate AD performance, a sub-objective was to evaluate the biogas potential in the different substrates.

**Materials and methods**

**Substrates**

Food waste from the local campus canteen in Uppsala, Sweden, was collected, homogenized and stored at −20 °C until use. Faeces were collected daily in plastic bags and kept at −20 °C until use. Inoculum for AD was collected from a sewage sludge digester at the local wastewater treatment plant (Kungsängen, Uppsala, Sweden). The inoculum was left to de-gas for 3 days at 37 °C under anaerobic conditions before use.

**BSF composting**

Approximately 10 000 five-day-old black soldier fly larvae were added to 5200 g thawed homogenized food waste and to 5800 g thawed and homogenised faecal material. The BSF composting of the mixtures was performed for 14 days at room temperature. Upon finishing the composting, the larvae were separated from the composting residues using a shaker table and both the larvae and the composting residues were stored at −20 °C until use.

**Biomethane potential**

Batch experiments for biomethane potential were set up using the Automatic Methane Potential Test System II (AMPTS II; Bioproduct Control AB, Lund, Sweden) and were carried out in 600 mL serum bottles filled with 1.2 g VS (total volatile solids) substrate (2.4 g VS L−1), 3.6 g VS inoculum (7.2 g VS L−1) and tap water to a final volume of 400 mL. The headspace was flushed with N2. Triplicate batch tests for each substrate, a blank for the inoculum and cellulose as a positive control, to ensure that the inoculum had the anticipated activity, were conducted for 16–22 days at 37 °C under stirring (130 rpm). Methane production was continuously monitored and reported at 0 °C, 1 atm, after passing the gas through 7 n NaOH to trap the CO2. Methane production attributable to the inoculum was subtracted when calculating cumulative methane production. A built-in algorithm in AMPTSII compensated for the effect of N2 as flush gas.

**Methane concentration of biogas**

Separate biomethane potential tests were performed to assess the methane concentration in the biogas. The AD experiments were conducted in 300 mL serum glass bottles filled with 0.6 g VS substrate (2.4 g VS L−1), 1.7 g VS inoculum (7.2 g VS L−1) and tap water to a final volume of 200 mL, and the headspace was flushed with N2. Each serum glass bottle was sealed with a gas collection bag connected to the top. Triplicate batch tests for each substrate and a blank for the inoculum were conducted for 22 days at 37 °C. The bottles were shaken manually once a day for the first week and later every couple of days throughout the experiment. The methane concentration in the gas produced was measured using an Einhorn fermentation saccharometer filled with 7 n NaOH to trap the CO2 (Jarvis et al., 1995). When calculating the methane concentration of the gas produced, the contribution of N2 in the total volume of accumulated gas was subtracted from the total.

**Physicochemical analysis**

The samples were dried at 80 °C for 48 h for total solids (TS) measurements and incinerated in a muffle oven at 550 °C for 4 h for VS measurements. For total N analysis, the samples were boiled in concentrated sulphuric acid according to the
The method described in Lalander et al. (2015). The samples were then diluted 50-fold in de-ionized water, prior to digestion using Spectroquant® Crack-Set 20 (1.14963.0001). The nitrate concentration was determined at 340 nm using Spectroquant® nitrate test with concentration range 0.4–25 mg L$^{-1}$ (1.09713.0002).

**Calculations**

The total carbon content of the substrates was estimated as (Haug, 1980):

$$\% \text{ carbon} = \frac{100 - \% \text{ ash}}{1.8}$$  \hspace{1cm} (1)

In order to get a more representative value of total cumulative methane production ($V$) from the different substrates, methane production was described by a simple model in which gas accumulation was assumed to follow first-order kinetics (Wang et al., 2015):

$$V = V_f(1 - e^{-kt})$$  \hspace{1cm} (2)

where $V_f$ is final methane volume, $k$ is a rate constant (d$^{-1}$) and $t$ is time (d).

Modelled daily cumulative gas production of the inoculum was subtracted from daily cumulative gas production of the substrates.

**Economic assessment of treatment strategies**

Four treatment strategies, treating food waste and faeces separately, were compared: (i) composting, (ii) BSF treatment, (iii) AD and (iv) BSF treatment followed by AD (BSF + AD). Thus, eight scenarios were assessed in total (Fig. 1).

The composting scenario was used as a reference treatment, as this is a common way of treating organic waste worldwide today. Literature values of the treatment efficiency were used for the different substrates. The other three strategies used values obtained in the experiments conducted in this study. The assessment was based on 1 t of food or faeces. Prices relevant for Swedish conditions were used in the assessment, as the study was conducted in a Swedish context. For the price of compost, the value in kg of VS was calculated for commercially available compost in Sweden, and this price (€ kg VS$^{-1}$) was also used for the BSF compost. Two subscenarios were considered for the AD and BSF + AD scenarios: a *vehicle gas scenario*, in which the biogas is upgraded to vehicle gas grade, and an *electricity scenario*, in which the biogas is used for combined heat and power production using a gas turbine. The heat produced was not valorized in the study. Only the revenues were considered in the assessment, which was intended to demonstrate the maximum treatment cost that could be supported in the respective scenario.

**Results**

**Physicochemical parameters of substrates**

The VS was reduced by a similar amount (~7 percentage points) for both food waste and faeces upon BSF composting, but the VS content in food waste was

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Fig. 1 Schematic representation of the four treatment strategies, where the green boxes represent the products generated in each strategy. In AD and BSF + AD, there were two possible products for the methane; in scenario A, the methane was upgraded to vehicle gas, while in scenario B, it was converted to electricity. BSF, black soldier fly; AD, anaerobic digestion.
higher than that in faeces at the start of the experiment (Table 1).

**Biomethane potential of substrates**

Food waste had the highest biomethane potential (>400 NmL g VS\(^{-1}\)) and a methane concentration in the biogas of 64% (Fig. 2 and Table 2). The biomethane potential of the BSF-treated food waste was ~78% of the biomethane potential in fresh food waste, but the methane concentration was not significantly different.

The biomethane potential of faeces found in this study (~350 NmL g VS\(^{-1}\)) was almost the same as for BSF-treated food waste, and had a methane concentration of 60%. The BSF-treated faeces had a biomethane potential which was around 54% lower than that of fresh faeces. Furthermore, the methane concentration in the biogas from BSF-treated faeces (55%) was significantly lower than in biogas from the other substrates (~60–64%).

**Economic assessment**

In the composting scenario, only one product was obtained (compost), while compost (treatment residue) and larval biomass (larval meal) were obtained in the BSF treatment scenario. The AD strategy generated methane and digestate, while methane, compost and larval biomass were generated in the BSF + AD scenario (Table 3).

The highest value for both the food waste and human faeces was obtained in the vehicle gas scenario of the

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**Table 1** Physicochemical parameters of the substrates used

|                     | TS (%) | VS (% of TS) | Total C (% of TS) | Total N (% of TS) | C : N ratio |
|---------------------|--------|--------------|-------------------|------------------|-------------|
|                     | Average (n = 3) SE | Average (n = 3) SE | Calculated | Average (n = 3) SE | Calculated |
| Food waste          | 24.5 0.2 | 92.5 0.4 | 0.4 51.4 | 5.0 0.3 | 10.3 |
| Faeces              | 21.9 0.4 | 87.1 0.1 | 0.1 48.4 | 5.7 0.1 | 8.5 |
| BSF food waste      | 51.7 0.4 | 85.4 0.1 | 0.1 47.4 | 7.6 0.4 | 6.2 |
| BSF faeces          | 67.1 0.3 | 79.8 0.2 | 0.2 44.3 | 12.5 1.8 | 1.8 |

SE, standard error.

**Table 2** Cumulative biomethane production [experimental value is the average value of three measurements at the end of the experiment (termination day varied for each replicate) and model value is the value the model predicted at day 40 of digestion (NmL g VS\(^{-1}\))] and methane concentration of the biogas produced from the different substrates: fly larvae-treated food waste (BSF food waste), fly larvae-treated faeces (BSF faeces), fresh food waste (food waste) and fresh human faeces (faeces)

|                     | Accumulated methane production (NmL g VS\(^{-1}\)) | Methane conc. (%) |
|---------------------|--------------------------------------------------|-----------------|
|                     | Average (n = 3) SE | Max SE | k | Average SE |
| Food waste          | 401.8 14.5 | 416.7*** | 3.6 0.42*** | 64.1* 0.2 |
| Faeces              | 338.5 17.4 | 347.8*** | 3.6 0.44*** | 60.0* 1.2 |
| BSF food waste      | 322.6 6.4  | 326.3*** | 1.3 0.39*** | 61.4* 0.4 |
| BSF faeces          | 178.9 7.1  | 188.0*** | 1.3 0.17*** | 55.2b 0.7 |

SE, standard error.

Values with different letters differ significantly (P > 0.5). Significance level of model coefficients: ***P < 0.001.

**Fig. 2** Mean \((n = 3)\) cumulative methane production (NmL g VS\(^{-1}\)) in cellulose and in the different substrates over the days of digestion: fly larvae-treated food waste (BSF food waste), fly larvae-treated faeces (BSF faeces), fresh food waste (food waste) and fresh human faeces (faeces); error bars represent the standard error and the grey lines the model fit. BSF, black soldier fly.
BSF + AD strategy, in which the food and faeces were treated by fly larvae and the treatment residue was digested (Table 4).

For the electricity scenario, the value of the products generated was considerably lower for the same treatment strategy. For example, for food waste, the total value on converting the methane to electricity was €31 per tonne of treated material, as opposed to €137 per tonne when upgrading to vehicle gas. For food waste, the value of the products generated in the AD strategy and the BSF treatment strategy was similar (€137 and €138 per tonne), while for faeces, a higher value was generated in the BSF treatment strategy (€126 per tonne as opposed to €99 per tonne for the AD strategy).

Thermophilic composting yielded the least valuable products. On converting the methane to electricity, the AD strategy yielded equally low-value products to thermophilic composting.

Discussion

Physicochemical properties of the substrates

In composting of faeces and food waste, addition of carbon-rich material can improve the composting process and decrease ammonia emissions, as the optimal C : N ratio is considered to be 10 : 1–25 : 1 (Guo et al., 2012), compared with the 10.3 or less found in this study (Table 1). However, this does not appear to be the case for fly larvae composting, in which the degradation rate of material was very high (<55% on VS basis), despite the low C : N ratio in both food waste and faeces (Tables 1 and 3). The C : N ratio decreased during BSF composting and such a decrease generally indicates that the stability of the material has increased, even if it is not an absolute measure of compost maturity (Boulter et al., 2000). A stability evaluation of the material leaving the BSF composter indicated that it was still immature, as the Rottegrad/self-heating test reached temperatures above 60°C within 24 h, which is comparable to results for raw compost (data not shown). The waste-to-biomass conversion rate was quite high for both substrates, around 35% on a TS basis.

Biomethane potential

Fresh food waste had a higher biomethane potential (20% higher) than fresh faeces, and both the VS content and C : N ratio of the faeces were slightly lower than in food waste (Table 1). This was expected, as faeces are food waste that has been degraded in the human digestive system. The potential of food waste, as well as the potential observed for cellulose (€300 NmL g VS⁻¹), was within the range reported in other studies (Hansen et al., 2004; Zhang et al., 2007). The potential of faeces was similar to the value reported for an high-strength undiluted human excreta simulant digested with a total
ammonium nitrogen (TAN) acclimated inoculum [370 NmL g⁻¹ chemical oxygen demand (COD)] (Colón et al., 2015).

The biomethane potential of faeces was reduced more by BSF treatment (by 50%; Fig. 1) than that of food waste (~20%) (Table 2). Even though there was a large difference in biomethane potential, the waste-to-biomass conversion rate was more or less the same for both substrates. This indicates that the nutrients required for larval growth were equally present in both substrates, but that the larvae used up more of the total available nutrients in the faeces than in the food waste for the same amount of growth. After BSF composting, there were still quite a lot of nutrients in the food waste for the microbial consortium involved in biogas production, while there were fewer nutrients left in the BSF-treated faeces.

Despite fresh food waste having considerably higher biomethane potential (20% higher) than fresh faeces, the BSF-treated food waste and fresh faeces had similar methane potential and these substrates also had similar VS percentage (around 85–87% on TS basis). However, the BSF-treated food waste had a lower C : N ratio (6.2) than fresh faeces (8.5), which indicates that BSF-composted food waste was more stabilized than fresh faeces. The BSF-treated faeces had quite low biomethane potential and the methane concentration was significantly lower (P < 0.05) than for the other substrates. The VS percentage (close to 80% on TS basis) and C : N ratio (3.5) in BSF-treated faeces were also lower in BSF-treated food waste and fresh faeces (Table 1).

The biomethane potential test of a substrate only indicates the potential in favourable conditions, where nutrients and active microbes are provided by the inoculum. The methane yield and conditions for achieving a stable biogas process during continuous operation, such as in full-scale biogas plants, will depend on, for example co-digestion with other substrates, the relative proportions of substrates, the hydraulic retention time and the organic loading rate (Mata-Alvarez et al., 2000). The residues from BSF-treated food and faeces both had a high TS concentration (~50%), which would require dilution with co-substrates with a lower TS concentration to manage operations in continuously stirred tank reactors. Thus, further studies with continuous biogas processes are necessary to validate the performance of BSF-treated food and faeces.

**Economic assessment**

Although BSF + AD resulted in the highest value products, this does not necessarily mean it is the most economically feasible strategy, as the cost of treatment was not taken into account in this study. The economic assessment conducted in this study should be viewed as an estimate of the economic space within which each treatment strategy has to operate in order to maintain economic viability.

The costs incurred with a BSF + AD treatment system depend on several factors. First of all, the actual cost of a novel system such as BSF treatment is very difficult to estimate, as no information is available to date. In order for biogas to be used as vehicle gas, it has to be upgraded, that is by removing CO₂ and other impurities so that the heating value is increased, followed by heavy compression. The commercially available biogas...
upgrading technologies commonly used at present are water scrubbing, amine scrubbing, pressure swing adsorption and gas separation membranes (Awe et al., 2017). The upgrading costs vary depending on the scale, requirements on gas purity grade, local conditions, etc. According to Sun et al. (2015), the investment cost of different technologies does not differ significantly. The investment cost for water scrubbing varies between ~200 and 900 € kWh⁻¹ for a plant size of 2000 and 100 m³ h⁻¹, respectively. The corresponding operating and maintenance costs are ~0.4 and 0.7 € cent kWh⁻¹, respectively. Thus, the larger the plant, the lower the cost per unit biogas processed. However, vehicle gas still competes with the price of petrol, and hence, the maximum cost of upgrading while still being economically viable will depend on the price of petrol (Palm, 2010).

This means that if there is already an existing large-scale digestion plant where biogas is upgraded to vehicle grade and it has the capacity to treat more waste, the most economically favourable treatment strategy for food waste could be AD or even the BSF + AD option, if a BSF treatment plant is attached to an existing large-scale digestion plant. For faeces, however, the treatment strategy with the highest economic potential is BSF treatment. If there is no digestion plant available, AD may not be the best option, especially in low- and middle-income countries. In a review of the history and future of AD in low-income countries, Bond & Templeton (2011) found that around 50% of AD plants installed since the 1970s in low-income countries were not operational for many reasons, but mainly lack of maintenance. Those authors concluded that for successful implementation of an AD plant in low-income countries, considerable government involvement is required to keep the support networks for maintenance and repair functioning over time. As mentioned previously, most local authorities in low- and middle-income countries are not currently able to supply adequate waste management services to their citizens. With this in mind, the BSF technology has several features that make it of particular interest in low- and middle-income countries, for example it is relatively simple and does not require sophisticated infrastructure, while it still generates valuable products and could be operated by a scheme that allows the involvement of the private sector. Additionally, a flexible waste treatment is possible if introducing a semi-centralized treatment strategy suggested by Diener et al. (2015): the BSF minilarvae required for the treatment is produced centrally, while the BSF composting of the waste is conducted at the place where it is generated. If the production of minilarvae is consistently high, the volumes of the waste can vary without any great impact on the treatment. This makes this treatment technology adaptable to waste volume changes. A drawback of the BSF technology in colder climates is that the production of minilarvae has to be performed in greenhouses, which, depending on the source of electricity, may have a negative environmental impact (Halloran et al., 2016). Furthermore, the waste-to-biomass conversion rate was high for the wastes evaluated in this study (around 35% on a TS basis, Table 3), converting a large fraction of the waste into potential feed. For some wastes (e.g. vegetable wastes), the conversion rate, and subsequently the value generated in BSF composting, would be lower. Although it is likely that it would also generate less biogas and thus ending up with the same results as in this study.

Conclusions

Black soldier fly larvae treatment decreased the biomethane potential of food waste by around 20%, while it decreased that of faeces by 50%.

In this economic assessment where the production costs were not taken into account, it was found that BSF treatment followed by AD yielded the highest value products when the biogas was upgraded to vehicle grade. In a large-scale digestion plant the upgrading process would be economically viable, but in small-scale digestion plants, it is unlikely that this cost would be covered. Where no large-scale digestion plant exists, BSF treatment is likely the most economically favourable.

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