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# A Review of the Use of Black Soldier Fly Larvae, *Hermetia illucens* (Diptera: Stratiomyidae), to Compost Organic Waste in Tropical Regions

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## Abstract

*Hermetia illucens* (L., 1758) is a fly of the family Stratiomyidae frequently found in tropical zones. Adult flies are not considered pathogens as they are incapable of biting and feeding thus not transmitting sicknesses to humans. The larval stage feeds off organic matter and offer a rich protein source naturally consumed by animals. The use of black soldier fly (BSF) larvae to treat organic waste is growing around the world. This is especially true for tropical low- and middle-income countries as their favourable climate conditions mean that the BSF technology has significant potential to solve existing problems associated with a poorly developed sanitation infrastructure. In this study, we evaluate the feasibility, benefits and limitations of implementing BSF projects in tropical regions using Belem, in Brazil, as a case study. Black soldier fly prepupae, arising from the waste reduction process, can be used as animal feed. It therefore offers potential to promote regional development, create jobs and dispose of organic waste locally. Legal requirements as outlined in the Brazilian National Policy on Waste offer further incentives. However, more studies are needed to compare BSF waste reduction efficiency and prepupae yield to other technologies such as traditional composting and vermiculture, which can inform the decision-making for implementation of organic waste treatment facilities.

## Introduction

The field of applied entomology has been growing in importance in recent years. While it has traditionally focused on using insect predators for biological control of pest species in agro-ecological systems (Cock *et al* 2016, Van Lenteren *et al* 2018), more emphasis is now also placed on using insects for developing biologically inspired technologies (Gorb 2011, Lenau *et al* 2018), as alternative food sources for production animals and humans (DeFoliart 1989, Van Huis 2013) and for reuse organic waste (Diener *et al* 2011a, b). In terms of the latter, black soldier fly (BSF) larvae, *Hermetia illucens* (L., 1758) (Diptera: Stratiomyidae), are particularly interesting as they offer a cost-effective potential alternative for recycling biological waste. The flies can be found tropical and subtropical as well as some temperature zones. Adult flies do not have mouthparts, stingers or digestive organs and are thus incapable of attacking and feeding (Park 2015, Al-Qazzaz *et al* 2016). This in turn means that even if black soldier flies get in contact with food, they, unlike house flies, do not transmit pathogens from waste to humans (Banks *et al* 2014, Kenis *et al* 2014, Dortmans 2015).

Many studies have pointed out BSF's potential to convert municipal solid waste, pig manure, kitchen waste, human faeces, fruit and vegetable, rice straw and other organic materials into a stable and valuable product (Diener *et al*

2009b, 2011a, b, Lalander *et al* 2013, Nguyen *et al* 2015, Manurung *et al* 2016, Dortmans *et al* 2017). Treatment with black soldier fly larvae can also reduce the half-life of pharmaceutical substances (Lalander *et al* 2016) and nutrients such as nitrogen and phosphor from waste (Myers *et al* 2008). The fly's prepupal stage, i.e. the last larval stage, is a nutritious source of proteins that can be exploited as animal feed for poultry, pigs, fish and amphibians, and thereby generate additional income (ST-Hilaire *et al* 2007a, b, Diener *et al* 2011a, b, Nguyen *et al* 2015, Park 2015, Spranghers *et al* 2016). There have been studies on food security pointing to the usage of insects, such as BSF larvae, as an important source of protein for some countries in Africa and Asia (DeFoliart 1989). Insects, such as BSF, meet nutritional requirements for both animals and humans as they are rich in vitamins, micronutrients and saturated and polyunsaturated fatty acids (Rumpold & Schlüter 2013, Van Huis 2013).

However, the BSF technology is not yet a well-established technology for treating organic matter and transforming it into a useful product, even though substantial initial investments are not needed (Manurung *et al* 2016). The three most used organic conversion processes are composting, vermicomposting and biomethanation (organic material is microbiologically converted under anaerobic conditions to biogas) (Diener *et al* 2009a, 2011a). The BSF technology has the potential to outperform these methods in tropical regions, but more information on the bioconversion efficiency of agricultural waste, municipal solid waste (the organic fraction), excreta and faecal sludge in low- and middle-income countries is required (Lohri *et al* 2017). The potential benefits of the BSF technology is particularly large in developing countries in the tropics as these have climates favouring maggot development, while often also having poor waste disposal systems with unregulated waste disposal in streets, dumping sites, rivers and other areas (Lohri *et al* 2017). Unregulated waste disposal leads to environmental pollution such as disagreeable odour, greenhouse gas emissions, toxic substances leaching to soil and groundwater and attraction of vector borne diseases. Poor management of municipal solid waste may affect an entire population due to contamination of surface and underground water supplies. Inadequate solid waste disposal can also influence the local economy. For example, if waste management systems function properly, they can generate job opportunities and local economic development (Diener *et al* 2009a).

Brazil is a good example of a developing country that can benefit from usage of the BSF technology, because most of its territory is situated in the tropics and black soldier flies are naturally occurring in the wild. Furthermore, Brazil does not have an efficient traditional waste disposal system. These conditions are especially true of the Northern Region of the country (the Amazon region). The state of Para, the most populated State in the Amazon region accounting for about 8.3 million habitants throughout 144 municipalities, faces several challenges regarding waste disposal management (IBGE- Brazilian Institute of Geography & Statistics 2015). A total of 7 tonnes of waste are produced daily in the entire state, but only 5.4 tonnes/day are collected. Moreover, 35% is disposed in open dumping, 37% goes to controlled landfill dumping, whereas only 28% receives proper disposal management in sanitary landfill (Abrelpe 2015).

Despite the fact that the black soldier fly can be found in northern Brazil (Pujol-Luz *et al* 2008), there has, to our knowledge, only been a few limited studies using BSF larvae to treat organic waste on isolated farms in Brazil (Silva *et al* 2018, Teixeira Filho 2018). There is a need for more studies on the potential to treat organic waste from urban and large rural communities in Brazil. Thus, the present review aims to investigate the feasibility, benefits and limitations for a BSF project implementation in tropical regions using Belem as a case study.

## Black Soldier Fly Larvae as Animal Feed Source

The intense utilisation of soy meal or fishmeal has significant negative impacts on the environment. Hence, insects may play an important role in replacing them as a protein source (Sánchez-Muros *et al* 2014). Black soldier fly larvae are rich in lipids and oils which can be utilised to feed animals (Makkar *et al* 2014, Henry *et al* 2015, Spranghers *et al* 2016). A previous study demonstrated the feasibility of using BSF larvae to convert poultry waste into feedstuff for tilapia and catfish (Bondari & Sheppard 1981). There are other studies pointing out the feasibility of utilising prepupae as a source of fishmeal rich in protein. In the Republic of Guinea, for instance, BSF larvae have been reported to digest proteins and fats locked inside palm kernels. The proteins in these palms are not directly accessible to fish. However, if they are processed through BSF treatment, the resultant larvae can be used as fish feed. The authors also state that results from experiments open up possibilities to use BSF to compost other seed waste (Hem *et al* 2008). A case study presented in Mohd-Noor *et al* (2017) uses waste from coconut endosperm to feed BSF larvae and enrich its lipid and protein content. This is particularly interesting as the Para State is the largest producer of açaí palm, *Euterpe oleracea* Martius, in the country. In the process of extracting the açaí pulp, only 15% of the fruit is used in the production of açaí vine, while the remaining 85%, which is composed of fibres and seeds, is discarded (Melo *et al* 2017). As a result, thousands of tonnes of daily açaí palm waste is not correctly disposed of. There is, therefore, great potential to exploit the application of BSF larvae to compost açaí palm seeds and generate a new source of investment in the State. Tropical regions are rich in biodiversity of palm seeds; thus, other fruit can be used to convert palm kernel into animal ration.

Tropical countries, including Brazil, have a rich diversity of fish species, which can be cultivated in tanks (Junk *et al* 2007). Pirarucu fish, *Arapaima gigas* (Cuvier 1817), for example, could be fed through a mixed diet of fishmeal and BSF larvae (Imbiriba 2001, Oliveira *et al* 2012, Queiroz-de-Oliveira *et al* 2013). Using BSF prepupae to supplement fishmeal does not have a negative impact on fish development (Bondari & Sheppard 1981, Kroeckel *et al* 2012). For example, replacing fishmeal with a diet that contained up to 15% BSF larvae (protein content) did not have any negative effects on fishes' feed conversion ratio. Moreover, the same diet allowed a reduction of fishmeal from 36 to 27% and fish oil content from 13 to 8% (ST-Hilaire *et al* 2007b). Their results are significant because they might represent an alternative to decrease the expenses associated with fish food and make fish farming more attractive to rural communities.

Black soldier fly larvae can also be used to replace or supplement the diet of poultry and livestock, though more research still has to be done to estimate the quantities required to sustain growth (Teguia & Beynen 2005, Veldkamp & Bosch 2015). Two recent studies found that using BSF larvae as feed source for laying chicken can increase eggshell thickness, egg yolk and egg albumin (Barbosa-Filho *et al* 2018, Kawasaki *et al* 2019). Secci *et al* (2018) analysed the impact of replacing laying hen's soya-based diet with BSF larvae diet. The authors claim that BSF can be used as total substitute of traditional soya ration. However, this is only true when egg quality is the target. Other studies should address the effects on the entire animal. In addition, egg yolk from hen fed on BSF larvae presented lower cholesterol and similar fatty acids. Similar results were obtained with quails (Dalle Zotte *et al* 2019).

Black soldier fly larvae have been used as supplement food for swine (Newton *et al* 1977), where it can be used to both feed the animals and digest the manure produced (Newton *et al* 2005a, b, Veldkamp *et al* 2012). When used to treat manure, BSF larvae can reduce *Escherichia coli* (E. 1885) content from the compost (Liu *et al* 2008) although thermal treatment has to be given to the prepupae before they can be fed to animals. However, it is important to note that there are still concerns regarding manure composting and using the residual larvae to feed animals. Another benefit associated with a BSF larvae diet is the reduced use of land, water consumption and lower emission of greenhouse gases in comparison to livestock-derived products such as soy bean and maize (Rumpold & Schlüter 2013). Green and Popa (2012) compliments by affirming that the ammonia ($NH_4$) concentration can be 5–6 times higher than that in the initial substrate, which could be advantageous for waste processing facilities as substances such as $NH_4^+$ and $NH_3^-$ can easily be absorbed by plants and soil or recovered.

## Black Soldier Fly System Design and Insect Maintenance

A BSF system is not complex to build and can be adapted according to local requirements. There are two main parts of the system, the larvero, which is the place where larvae grow, and the fly house where adult flies will live and reproduce (Fig 1). The initial step is to acquire BSF eggs, which can be obtained in the market or captured in the wild of most tropical regions. In terms of Brazil, there are two studies which captured BSF's eggs in Belem (Silva *et al* 2018) and Amazonas (Teixeira Filho 2018), both in the Amazon region. However, BSF can also be found in other states outside the amazon region such as Minas Gerais and in the northeast region.

For capturing eggs in the wild, an "egg trap" can be set up. An egg trap consists of a rearing box (plastic box), food source (vegetables, fruit, manure or other organic matter), a nylon screen and corrugated cardboard pieces. Basically, one should place the rearing box filled with a food source out in the open to attract BSF females. The nylon net is used to allow spreading odour and block potential parasitic and predatory insects from entering the system. The cardboard pieces are placed on top of the nylon net, close to the food source (Sripontan *et al* 2017). The female flies will deposit their eggs on corrugated cardboard where they can be extracted from and placed in the larvero system (Boaru *et al* 2019). Sripontan *et al* (2017) analysed different food diets to attract BSF females and found that oviposition was higher near fruit waste traps in comparison to animal manure. However, many types of decaying organic diets can be used to attract BSF females.

Middle- to large-scale or urban facilities might have their own nursery unit to provide eggs for the treatment facility. The adult flies are usually kept in a screened cage separately from the larvero. Cicková and co-workers (Čičková *et al* 2012), for example, utilised two experimental metal cages, one with dimensions of 30 × 30 × 30 cm with a capacity of 1000–1500 pupae and another with dimensions of 60 × 80 × 145 cm capable of holding 25,000 pupae. Their oviposition scheme used a food diet chosen to attract females to deposit their eggs on a cardboard structure. However, in order to avoid problems associated with inbreeding, self-contained facilities should occasionally be supplemented with wild-caught eggs or larvae.

The recommendation for the larvero is to maintain a regular food supply, a drainage system for leachates and a ramp where the larvae can crawl out for the prepupae stage, which also ensures easy separation of pupae from larvae (Diener *et al* 2011a). The mass of BSF larvae required per system can be estimated by Eq. 1 (Dortmans *et al* 2017):

$$\frac{M_{\mathrm{system}} = L_{\mathrm{system}} \times \mathrm{TM}_{\mathrm{cont}}}{\mathrm{TL}_{\mathrm{system}}} \qquad (1)$$

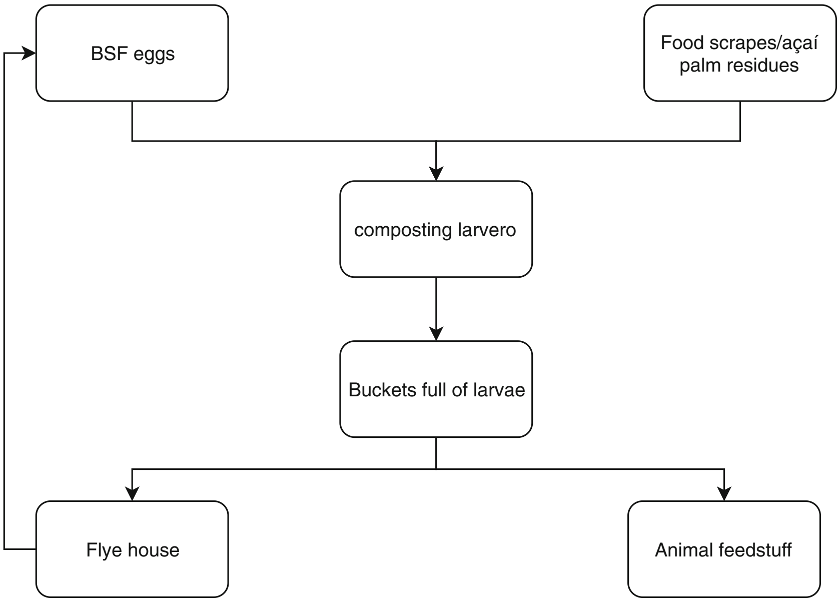

Fig 1 Flow diagram outlining the process.

where

| | |
|---|---|
| $M_{\text{system}}$ | mass of BSF larvae required per composting system; |
| $L_{\text{system}}$ | number of larvae needed per system; this number is roughly 600-800 larvae/Kg of wet waste; |
| $\text{TM}_{\text{cont}}$ | total mass of larvae in the rearing container, which is simply the weight of larvae in the composting box; and |
| $\text{TL}_{\text{system}}$ | total number of larvae in the system. This can be determined multiplying the $\text{TM}_{\text{cont}}$ by number of larvae in a given sample then dividing it by the mass of the sample. |

For household-sized systems, the growing of larvae might be done in plastic buckets, which has to be adapted to include a ramp and drainage. Even a traditional three bucket composting bin scheme can be used to grow BSF larvae in the feeding phase, as used in a rural system reported by Silva *et al* (2018). For middle- to large-sized composting facilities, concrete basins with a ramp can be used too, but they are usually set for manure management (Sheppard *et al* 1994, Newton *et al* 2005a). The size varies with the amount of waste added to the system and the number of larvae within the system. The retention period depends on factors such as surrounding temperatures (Sheppard *et al* 2002), age at inoculation and type of material (Dortmans 2015). Anaerobic conditions can be avoided if the material height inside the container does not exceed 7.5–10 cm (Čičková *et al* 2015).

Dortmans (2015) used a 6.8-L bucket (0.25 m × 0.55 m × 0.5 m) in his experiment to compost 132 kg of waste in 47 days, but usually the larvae are ready to be harvested after 12 days (Dortmans *et al* 2017). Other authors adopted different volumes such as a 72-L bucket (Mutafela 2015) and a 37-L BSF reactor (Lalander *et al* 2014). For a small- to medium-scale project, it will be necessary to have containers with a volume above 75 L (UNC Institute for the Environment 2013). In addition, a recent study demonstrated that black soldier fly larvae strains from different parts of the world show distinct phenotypic plasticity (different development time and waste conversion efficiency) (Zhou *et al* 2013). These differences, therefore, must be accounted for before selection and establishment of the waste management system. We have identified two pilot studies using BSF larvae to compost in the Brazilian Amazon region, one bucket experiment in the State of Para (Silva *et al* 2018) and another lab-scale system in the Federal University of Amazonas, State of Amazonas (Teixeira Filho 2018). Both studies indicate significant potential to use these insects to compost organic matter and produce an added-value by-product. Thus, we recommend conducting a pilot project with BSF larvae to determine its local feasibility as a waste management tool in cities to compost urban wastes.

There are large-scale facilities using BSF larvae to produce protein that treat up to 200 tonnes of waste/day (Diener *et al* 2015). However, information on the design and operational procedures of successful large existing BSF treatment facilities are commercially sensitive and not openly shared (Lohri *et al* 2017). A study in Costa Rica estimated a treatment area of a facility to compost 3 tonnes/day of municipal organic waste at about 930 $m^2$ plus the facility area giving roughly 3.2-kg compost per square metre per day (Diener *et al* 2009a), compared to vermicomposting with an estimated 2.4-kg compost per square metre per day based on a much smaller scale plant (Marsh 2009). Recently, Lalander *et al* (2018) compared three strategies for composting food waste and faeces through vermicomposting, BSF larvae and BSF larvae integrated with an anaerobic digestion. The latter configuration presented the highest final product value due to the combination of biogas, animal feedstuff and fertilisers whereas vermicomposting had the lowest final product value. However, more studies that directly compare the two methods, when it comes to area requirements, waste conversion and costs, are needed.

Figure 2 illustrates industrial-scale design for the larvero and mating cage, whereas Fig 3 shows a house-made larvero. Figure 2 comes from Dortmans *et al* (2017), who present design systems and procedures for larger facilities based on an operational facility in Indonesia. On this system, the larvae are manually collected and transported to other stages. Other systems might have a type of ramp, so the larvae can crawl out larvero by themselves. The design in Fig 3 is similar to the one proposed by Diener *et al* (2011a). On this design, the larvae will migrate to the bucket for pupation (natural process); the prepupae is then collected from the bucket and manually placed in the fly house (some can be diverted to other destinations such as animal feed). Food is added to the larvero manually by opening the lid and placing a layer of approximately 5 cm of waste spread evenly over the area. The main weakness of this type of larvero is the drainage system which requires constant maintenance not to clog up. Alternative designs are easily found online thus constructing the system should not be a problem to small and middle rural communities.

The costs for constructing the BSF system will depend on the scale planned (UNC Institute for the Environment 2013). Nonetheless, there are common requirements that must be accounted for independent of which technology is chosen to process organic waste. Table 1 summarises these items for an urban organic treatment system. Dortmans *et al* (2017) provide a wider list of components for BSF systems and equations needed to dimensioning the facility. Rural projects may be simplified without mechanised equipment, huge infrastructure, trucks, office and other items. Determining the exact dimensions can only be done through a pilot project with detailed field work assessment of local waste production, the local populations' preparedness to separate organic from non-organic waste, environmental conditions and landscape characteristics.

## Application of BSF technology in Belem, Brazil

### *Brazilian National Solid Waste Policy and Black Soldier Fly Technology*

One principle established in the Brazilian National Waste Policy (BNWP), law no. 12,305/2010, section VII, is the recognition of solid waste, which can be recycled or reutilised, as an economic tool for generating job opportunities, extra income and social value. Furthermore, art. 36, section V, of the law determines that the municipality waste management plan must contain alternatives to correctly treat organic content from domestic wastes (Brazil 2010). Waste treatment is not only an environmental concern; it also represents a health and safety issue. Social inclusion and job opportunities for people who work as waste scavengers on dumping sites is also an objective of the Brazilian Policy on Waste (Brazil 2010).

In Costa Rica, as mentioned in the previous section, the BSF method was studied to process municipal organic waste with good results (Diener *et al* 2009a, b, 2011a, b) and BSF has frequently been used in many countries to compost manure and faecal sludge (Sheppard *et al* 1994, Lalander *et al* 2013). It provides opportunities for small businesses and individuals to earn extra income by collecting and treating organic residues (Diener *et al* 2009a, b, 2011a). Environmental licenses (installation and operational licenses), as set out by the National Environmental Council (CONAMA)'s Resolution no. 237/1997 for up-scaling projects to treat waste, may have simplified the license processes. Small projects might not even need environmental licenses to operate, but this can only be determined by local environmental agencies.

Fig 2 Medium industrial-size scheme for larvero (right) and mating cage (left). Source: (Dortmans *et al* 2017).

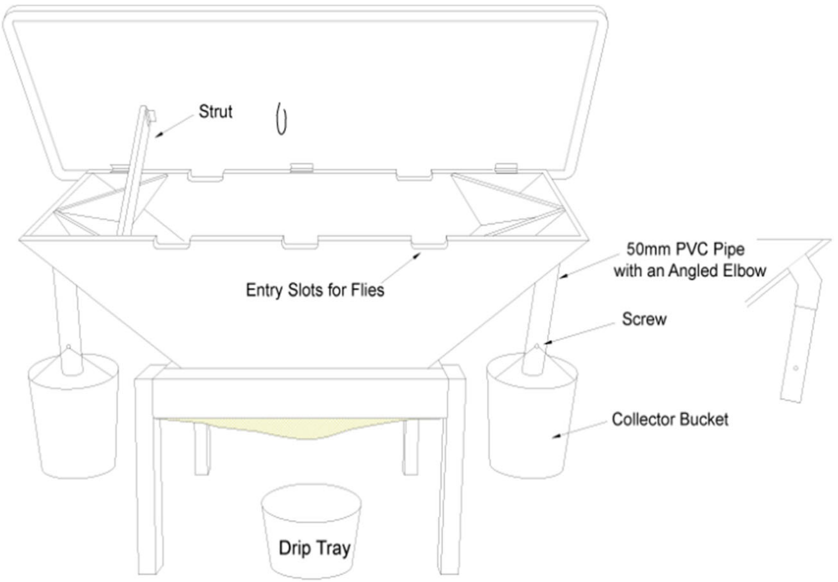

Fig 3 House-made small-scale larvero (the Filterbug Bin). With permission from Peter Barnard and www.blacksoldierflyfarming.com. Source: (BSF Farming 2012).

Prepupae also have to be analysed according to the standards of the Ministry of Agriculture, Livestock and Supply's (MAPA) normative instruction no. 04/2007 about best practices to produce animal food and hygiene conditions of the facilities (MAPA 2007). Residue from BSF larvae can be used as fertiliser for crop production (UNC Institute for the Environment 2013, Lohri *et al* 2017, Boaru *et al* 2018), but this also requires approval from regulations such as the federal decree no. 4,954/2004 and the MAPA normative instruction no. 25/2009 both of which concerns the usage of biofertilisers in agriculture (Brazil 2004, MAPA 2007). In Sarpong *et al* (2019), BSF composting residue presented good standard quality to be used as a soil fertiliser. The fly's residue is similar to vermicomposting's, which is a mixture of unassimilated material and BSF larvae excrement (Rosmiati *et al* 2017). Thus, it might require drying and screening before application on the soil. All those regulations must not be viewed as obstacles to implement projects on waste management such as composting, vermiculture and black soldier fly larvae. Instead, they are tools to guarantee the quality of the final product and the safety of operational facilities.

Table 1 General items for organic waste treatment system.

| General requirements | BSF facility |
|---|---|
| Land | Residue maturation area (larvero) |
| Collection truck and fuel | Oven for killing and drying of prepupae |
| Maintenance of infrastructure/truck | Fly colony |
| Infrastructure | Fly house |
| Equipment | |
| Tool shed | |
| Sanitary facility | |
| Sorting area | |
| Storage of rejects/recyclables | |
| Screening and bagging of residue | |
| Office | |
| Expendables | |
| Salaries | |
| Training | |
| Telephone/water/electricity | |

The BSF technology is therefore a novel and potentially valuable tool to achieve the principles and objectives established in the Brazilian National Policy on Solid Waste, but further studies are required to compare its final products (prepupae and residue) to applied regulations regarding solid waste.

### *Temperature and Humidity*

Temperature and humidity are two key factors that influence feeding, development and the life cycle of black soldier flies (Dortmans *et al* 2017). The survival temperature for BSF larvae ranges from 0 to 45 °C, although the ideal temperature for food consumption is around 30–35 °C (UNC Institute for the Environment 2013). A study on bioconversion of human faeces by BSF stated ideal conditions varying from 25 to 30 °C (Lalander *et al* 2013). Ideal conditions for reproduction were observed at 32 °C, but temperatures ranging from 15 to 47 °C were tolerated (Diener *et al* 2011a). However, the majority of studies work with temperature and humidity around 27 °C and 67%, respectively (Diener *et al* 2009b, Banks *et al* 2014), or temperatures in the range of 20–35 °C and humidity above 30% (Nguyen *et al* 2015). Larvae, reared at temperatures varying between 27 and 32 °C, have a final weight 30% greater than those reared at higher or lower temperatures, though they require slightly more hours to develop in these temperatures (27–32 °C) (Harnden & Tomberlin 2016). In addition to that, females weigh 17–19% more than males in temperature conditions ranging from 27 to 30 °C (Tomberlin *et al* 2009). Humidity affects BSF egg eclosion and an environment with 70% relative humidity (RH) may increase the survival of adult flies by 2 to 3 days, while low RH increase the mortality of larvae (Holmes *et al* 2012).

Northern Brazil has a tropical climate with a relatively stable temperature and humidity throughout the year. The temperature for the State of Para is always greater than 18 °C with the annual mean temperature ranging between 23 and 26 °C. Humidity also presents high values above 80% with an annual mean of 90% (Silva & Souza 2016).

Climatic conditions are thus within optimal conditions for reproduction and feeding of these insects, which support the environmental potential to exploit BSF larvae technology in composting organic material in Belem and nearby cities. However, it is important to protect the treatment system (containers and greenhouse) from direct sunlight, because it can increase the temperature of the container and compromise the development and hence compost efficiency of the BSF larvae. Heussler *et al* (2018) demonstrate that indoor rearing with artificial light is also possible. The authors studied the effect of three different light sources on fly's oviposition and longevity. While light source did not significantly affect laying of eggs, flies that grew under halogen lights experience half-life shorter than flies reared under LED lights. This might be related to the high temperature of halogen lights.

### *Organic Generation in Belem and Estimated Waste Reduction*

The lack of data regarding organic residue generation in Belem associated with the absence of selective collection is the major challenge for projecting and implementing composting techniques to the municipal waste disposal system in the city. For a pilot BSF project to compost organic residues in the city, it is, therefore, necessary to acquire data on the organic matter content of the waste. Restaurants, universities, public markets and other confined areas are preferable starting points to acquire data. Through a literature review, data on waste generation in a university, a restaurant, a public market and a private school was compiled (see Table 2). The waste generation ranged from 26 to 27,000 kg/day, at a university and a public market, respectively. Table 2 shows the percentage of the organic fraction that waste represented of the total, and the year in which that data was published.

The public market, Ver-o-Peso, has the highest organic waste generation and its total daily waste production is comparable to a neighbourhood in Belem with a population of 34,000 (Dos Santos *et al* 2014). The school and the university campus, on the other hand, produced from 26 to 85 kg/day, which suggests that a pilot project to study BSF on site would be more suitable to be implemented at these sites. Table 3 provides information about the amount of waste fed into different BSF systems, residue from those systems, waste reduction achieved, prepupal yield, feed conversion ratio and feed source for each project analysed. The organic waste reduction varied according to diet (feed source), the quantity of food added per larva (optimal feed ratio) and type of waste (wet or dry matter).

The final prepupal yield will depend on variables such as temperature and humidity in the system, egg eclosion, reproduction rates and other parameters. Diener *et al* (2011a) had on average, in favourable conditions, a prepupae yield of 0.3 kg/m$^2$/day (wet weight). However, they claim that prepupal yield of 0.8–1.0 kg can be achieved if the system receives a daily diet input of 15 kg of fresh municipal per square metre. Prepupae yield of 46 g/kg from poultry manure has been reported (Čičková *et al* 2012), but generally 1000 kg of manure generates about 200 kg of prepupae (Diener *et al* 2015). In other words, about 20% of organic material can be converted into biomass (see also Table 3) that can be used as animal feed and crop fertiliser or can be sold on to other local farms.

Waste conversion into prepupae biomass also depends on the type of waste given to larvae (Tschirner & Simon 2015) (Table 3). The reduction estimated here is, however, important because it demonstrates the potential to decrease the organic waste produced at a range of sites in Belem including restaurants, organic market and universities. Organic waste preferentially necessitates prompt processing and treatment due to risks of disease transmission and material putridness. Decentralised organic waste treatment systems using BSF is thus being proposed as an alternative to process organic waste in developing countries (Diener *et al* 2015). The waste treatment facility in Belem is located far from the urban centre, but smaller decentralised facilities distributed throughout the city would minimise the organic waste quantity directed to the inter-municipal sanitary landfill, especially concerning residues from açaí palm kernel whose production is widely distributed throughout the city. Lalander *et al* (2019) also suggest using abattoir waste with mixture of fruit and vegetable scraps as a suitable alternative to feed BSF larvae colonies and reduce urban organic waste. In light of that, the Ver-o-Peso supermarket and other public markets can be a valuable source of organic waste for a BSF composting facility. This will prolong the lifetime of the waste disposal facility and minimise environmental pollution associated with poor organic waste management. Moreover, through semi-centralised BSF larvae facilities, transportation expenses can be reduced with up to 60% (Diener *et al* 2015).

On-site pilot studies are necessary to investigate the insects' response to local conditions and to locate areas

Table 2 Characterisation of the data about waste production in Belem or nearby cities.

| Location | Organic waste (wet weight)/day | Percentage (%) | Year | Reference |
|---|---|---|---|---|
| City of Curuça | 515 kg | 52 | 2004 | (Cunha & Carneiro 2007) |
| Private school | 85 kg | 24.21 | 2010 | (Cristina & De Souza 2010) |
| UFPA campus[1] | 26 Kg | 41 | 2008 | (Cardoso *et al* 2009) |
| Ver-o-Peso Public Market | 27,000 kg[2] | – | 2012 | (Dos Santos *et al* 2014) |

[1] Only a small part of the campus. [2] Mean generation of 27.68 kg/person, 731 people who worked with organic material. 27.68 × 731 = 20234.08 kg/day

and potential benefits for construction of a semi-centralised waste management system in Belem.

## Challenges and Future Research

Here we have pointed out several benefits of using BSF to compost organic residues including efficient waste reduction, the capacity to degrade diverse types of food, income from selling prepupae as animal feed and creation of jobs and of the resulting financial value of the waste. However, challenges of using this technology also need to be taken into consideration in order to estimate its true potential for a project of any scale.

First, this technology is based on using living organisms to compost waste. Therefore, controlling the temperature and the heavy metal concentration in the compost and ensuring sufficient oxygen levels in the waste is required to guarantee survival of the insects (Diener *et al* 2011b). The majority of studies using this technology were conducted in developed countries and more research in developing countries is necessary to test its feasibility there (Bonso 2013). Another challenge is the public acceptance of using larvae in agriculture and as animal feed (Westerman & Bicudo 2005). The usage of larvae to feed freshwater fish and poultry is not generally a concern, because insects are a natural feed source for those animals (Van Huis 2013). Heavy metal accumulation in the food chain from prepupae fed to animals is also potentially a major concern and heavy metal–contaminated sources must therefore be controlled (Diener *et al*. 2011a, b). Future research must focus on developing ways to separate heavy metals from prepupae and residues.

In addition, on a small scale, labour requirements may be high and the market for the by-product is currently unknown. Regulation and nutritional standards for animal feeding or usage as compost on agricultural field may apply too and must be followed (Diener 2010, Mutafela 2015).

Table 3 Information about BSF projects from literature.

| Ref. | Local | Total amount of feed (dry weight) | Total amount of feed (wet weight) | Residue | Waste reduction (%) | Prepupal yield | Feed conversion ratio (%) | Feed source |
|---|---|---|---|---|---|---|---|---|
| (Diener *et al* 2011a) | Costa Rica | 151 kg | | 48 kg | 68 | 17.8 kg | 14.5 | MOW |
| (Dortmans 2015) | Sweden | – | 136 kg | 7.3 kg | 85 | 15.7 kg | 19.0* | FHF |
| (Dortmans 2015) | – | 32.9 kg | | 3.6 kg | 71 | 6.4 kg | 19.0* | FHF |
| (Dortmans 2015) | – | – | 136 kg | 7.7 kg | 85 | 15.5 kg | 18.9* | FHF |
| (Dortmans 2015) | – | 32.9 kg | | 4.1 kg | 71 | 6.3 kg | 18.9* | FHF |
| (Newton *et al* 2005b)** | USA | 67.8 kg | | 41.6 kg | 39 | 26.2 kg | 9.6 | PM |
| (Banks *et al* 2014) | England | | 658 g | 301 g | 54.2 | 108 g | 3.4 | HF |
| (Banks *et al* 2014) | – | | 721 g | 327 g | 54.6 | 131 g | 33.9 | HF |
| (Banks *et al* 2014) | – | | 390 g | 260.2 g | 33.4 | 8.5 g | 15.2 | HF |
| (Banks *et al* 2014) | – | | 482 g | 360.3 g | 25.2 | 11.3 g | 10.7 | HF |
| (Banks *et al* 2014) | – | | 437 g | 219.8 g | 49.7 | 65.3 g | 3.3 | HF |
| (Banks *et al* 2014) | – | | 483 g | 261.4 g | 45.8 | 110.7 g | 2.0 | HF |
| (Mutafela 2015) | – | 4.6 kg | | 2.8 kg | 37 | – | 32.73 | Manure |
| (Mutafela 2015) | – | 3.3 kg | | 2.7 kg | 16 | – | 13.60 | Manure |
| (Mutafela 2015) | Sweden | 2.0 kg | | 0.3 kg | 83 | – | 20.94 | Fruits |
| (Mutafela 2015) | – | 1.2 kg | | 0.3 kg | 74 | – | 13.94 | Fruits |

*MOW* municipal organic waste, *PM* pig manure, *FHF* food waste and human faeces, *HF* human faeces. *Biomass conversion rate in %, **calculations were done by Diener *et al* (2011a).

There is also a need for additional studies on the capacity of these insects to degrade agricultural waste such as coffee pulp (Lardé 1990), faecal sludge from sanitation facilities and on-site projects including small faecal waste from potential future sustainable dry toilet solutions (Lenau & Hesselberg 2015), municipal solid waste, excreta and all types of disposal management that leads to environmental impacts in developing countries (Diener 2010, Bonso 2013). Up-scaling this technology to a cost-effective system for bioconversion of municipal solid waste on a mass-rearing facility with steady, safe and reliable production of prepupae/compost will be a challenge (Bonso 2013, Van Huis 2013). Waste segregation is a key factor for accomplishing good results because it influences the effort required to separate the material and the final product (Diener *et al* 2009a, b). This will be a major challenge for treating municipal waste in Belem, because segregation of material at source is not a common practice in the city. Application of this technology (and any other on composting organic material) on a municipal waste treatment scale must be preceded by public education programmes on segregation and possible economic incentives. Finally, a study comparing installation/operation costs of the BSF system to other types of facilities (vermicomposting, composting and others) would also be beneficial. Such a study would allow a possible comparison of "unit cost per ton of waste processed per day." Table 4 gives an overview of possible challenges/limitations and benefits/opportunities for BSF systems.

## Conclusion

In this study, we have outlined the advantages of using black solider fly larvae to reduce organic waste, while simultaneously producing an income to the local population. For these reasons, interest in using BSF technology for organic waste treatment is growing around the world particularly in low- and middle-income countries due to favourable climate conditions, and existing problems associated with waste disposal. Some developing countries with studies concerning this technology are Costa Rica, Indonesia, Guinea and China. Most effort is concentrated on manure management and faecal sludge treatment facilities (Sheppard *et al* 1994, Lalander *et al* 2013), though the application of these insects to compost municipal solid waste and agro-industrial waste is rising (Diener *et al* 2011a, Dortmans *et al* 2017). The prepupae resulting from the process can be used as animal feed due to its rich protein and nutrient content. The high prices associated with animal food make the usage of black soldier fly larvae an interesting alternative to traditional animal feed, but other uses such as biodiesel production and agriculture are also feasible (Sánchez-Muros *et al* 2014). We argue that Brazil, where the black fly soldier fly is found in the wild, has a great potential for exploiting this technology because of its location, climate conditions, land availability and the political will expressed in the National Policy on Solid Waste. The city of Belem, in particular, has a relative constant temperature and humidity close to the optimum conditions for black soldier fly development and survival. Although the city is quite large without open spaces available to implement this

Table 4 Comparison of benefits/opportunities and limitations/challenges.

| Benefits and opportunities | Limitations and challenges |
|---|---|
| Prepupae as an alternative animal feed. | Current market for product is unknown. |
| Larvae can produce oil for biodiesel (Li *et al* 2011, Zheng *et al* 2012) and compost to agriculture. | Segregation at source needs to be fully established. |
| Possibility of generating jobs and extra income. | Possible regulations about the products. |
| Matches well with the principles and objectives on the Brazilian National Policy on Waste. | Necessity for monitoring environmental conditions and breeding parameters. |
| Waste reduction is faster than composting and minimises odour problems. | Needs more research on market value and enhanced production. |
| Larvae digest diverse types of residues and are more resistant to environmental changes than worms. | Potential build-up of heavy metal contamination on prepupae for animal feeding. |
| Sludge (faecal) treatment alternative. | May require a high initial investment (Mutafela 2015). |
| Black soldier flies are not pathogenic and can be found in the wild in Brazil. | |
| Potential to reduce salmonella, viruses and pharmaceutical substances in the waste. | |
| It can be used to manage animal manure. | |
| Reduce organic waste from organic public markets and increase landfill lifetime. | |
| Reduce nitrogen and phosphor from waste. | |
| Minimise environmental pollution. | |

technology near the city centre, decentralised stations could be used to receive and pre-treat the organic waste from public markets, school/universities and restaurants (Diener *et al* 2015). The next logical step is to set up local pilot projects to explore the feasibility, environmental and financial benefits in more detail.

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### Compliance with Ethical Standards

*Conflict of Interest* The authors declare that they have no conflict of interest.

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