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Global Experiences on Waste Processing with Black Soldier Fly (*Hermetia illucens*): From Technology to Business

Gabrielle Joly and Josiane Nikiema

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Global Experiences on Waste Processing with Black Soldier Fly (*Hermetia illucens*): From Technology to Business

Gabrielle Joly and Josiane Nikiema

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ACRONYMS AND ABBREVIATIONS

BSF	Black Soldier Fly
C	Carbon
CAD	Canadian Dollar
CH_4	Methane
CO_2	Carbon Dioxide
DM	Dry Matter
DW	Dry Weight
GHG	Greenhouse Gas
GWP	Global Warming Potential
IDR	Indonesian Rupiah
MSW	Municipal Solid Waste
N	Nitrogen
R&D	Research and Development
SDG	Sustainable Development Goal
USD	United States Dollar
WW	Wet Weight

SUMMARY

The black soldier fly (BSF) can cope with a wide range of environmental conditions and the adult fly is not a vector of disease. BSF larvae can consume different organic materials, including various organic wastes generated in large volumes within urban areas. By doing so, they reduce waste volume, grow into a protein-rich biomass and leave behind a nutrient-rich residue. The harvested larvae can then be used in formulating feed for monogastric animals such as poultry, fish and pigs. Given their high fat content, they may also be processed into high quality biodiesel. The waste residue could constitute a valuable soil conditioner. Therefore, the BSF-based technology is viewed as one of the most promising technologies for organic waste processing.

This report gives an extensive overview of the different aspects of BSF-based technology when used for organic waste processing. It describes the different process components, i.e. (1) waste preprocessing, (2) BSF breeding, (3) waste treatment, (4) product harvesting, and (5) post-treatment of the final products. For each of these key steps, the report describes recommended operating conditions and possible designs. It also reviews the economic, environmental, legal and social aspects of the BSF-based treatment method and presents four business examples on the implementation of the BSF technology in different parts of the world and at different scales. The analysis reveals that the BSF technology could be a promising business option for organic waste valorization. However, it highlights that most research has so far focused on the technical aspects of the technology, resulting in limited data on its economic and environmental performance in support of business start-ups and development.

1. INTRODUCTION

Waste management constitutes one of the most pressing challenges of the twenty-first century and plays a key role in sustainable development (Scheinberg et al. 2010; Wilson et al. 2015). As waste management is a cross-cutting issue, which impacts many aspects of societies, economies and the environment, addressing this challenge also contributes towards the achievement of more than half of the United Nations Sustainable Development Goals (SDGs) for 2030, including those related to health, climate change, food security, poverty alleviation, responsible consumption and production (Wilson et al. 2015). The global amount of waste generated is increasing rapidly due to population growth, rapid urbanization and economic growth associated with changes in consumption patterns (Karak et al. 2012; Wilson et al. 2015). Most of this growth is occurring in low- and middle-income countries. At the same time, natural resources are being depleted. This calls for a paradigm shift toward a circular economy focusing on ‘closing the loop’, which can be achieved through waste valorization (Lohri et al. 2017).

Organic waste recycling is often overlooked because the value of its products is perceived to be lower than that of other waste materials such as plastics, glass or metal (Scheinberg et al. 2010). However, treating organic waste in low-income countries, where it often accounts for the greatest fraction of the municipal solid waste (MSW) generated (typically 50 to 80%), would significantly improve the whole waste management system (Wilson et al. 2015; Lohri et al. 2017; Zurbrügg et al. 2018); in addition, health and environmental hazards related to inappropriate disposal practices would be reduced and nutrient loss would be avoided. Different technologies for the valorization of organic waste have been extensively studied and implemented successfully, the most widespread being composting and anaerobic digestion (Zurbrügg et al. 2018). However, in low- and middle-income countries, the implementation of these solutions has been hindered due to limited financial resources, lack of political support, poor legislative frameworks and legal barriers hampering the marketing of products from the valorization process, as well as the lack of viable business models (Ali 2004; Zurbrügg 2013). Therefore, promoting the value-adding opportunity of organic waste valorization and designing viable business models are crucial to make organic waste recycling more attractive (Rao et al. 2017).

The valorization of organic waste using the black soldier fly (BSF) has been promoted as a promising technology, especially in developing countries, as it combines waste reduction and value creation through the bioconversion of low-value organic waste into high-value energy-rich larvae that can be sold. This innovative technology consists of feeding organic waste to BSF larvae to reduce its volume and to recover nutrients. As the larvae feed, they grow into a highly nutritional biomass that can be harvested and further processed into animal feed ingredients or biodiesel, while the waste residue can also be postprocessed into biofertilizer. In addition to improving waste management, BSF technology could contribute to food security. Indeed, BSF larvae-based ingredients constitute a potential alternative to increasingly costly and highly unsustainable feed products (e.g. fishmeal and soybean meal), currently used in the animal production industry (St-Hilaire et al. 2007b; Newton et al. 2008; Salomone et al. 2017; Quilliam et al. 2017). By addressing two major global challenges, BSF waste treatment may constitute “the missing link in designing a circular economy” (van Huis et al. 2013).

As research on BSF technology for organic waste valorization is relatively recent, few comprehensive review of this technology is currently available. Therefore, this study provides an extensive overview of the BSF technology; it describes the status of the research, different aspects of this treatment method (technical, economic, environmental, social and so forth), compares it to other options for organic waste valorization, presents case studies on technology implementation and highlights the need for further research.

A thorough literature search was carried out in 2017 using the Web of Science and Science Direct databases, Google Scholars, as well as specific libraries, such as the Wiley Online Library, Sage Journals and Springer Link. The search strings used for the literature review included ‘black soldier fly’, ‘*Hermetia illucens*’ and ‘organic waste’. Additional publications were then identified based on the references used in the articles found through the database search. In total, more than 90 studies were selected and reviewed. In addition, BSF systems in Ghana and Sweden were visited and actors working with BSF technology were interviewed in order to provide concrete case studies of the implementation of a BSF system.

This analysis was guided by the following research questions:

(1) How does the waste treatment by BSF work?
(2) How is it implemented?
(3) How does such a system perform technically, economically and environmentally?
(4) What are the prospects and constraints associated with the implementation of BSF technology as a business?

2.THE BLACK SOLDIER FLY (BSF)

The BSF (*Hermetia illucens*), also known as latrine larva, is a dipterian from the Straiomyidae family (Diener 2010; Caruso et al. 2013; Dortmans et al. 2017; Lohri et al. 2017). It was originally native to the tropical region of Central and South America but has spread to other parts of the world through the transport of goods and human migrations (James 1935; Callan 1974; Leclercq 1997). Today, it is commonly found in tropical and warm temperate regions between latitudes 45°N and 40°S (Diener 2010; Caruso et al. 2013; Dortmans et al. 2017; Lohri et al. 2017).

The BSF has a short lifecycle of about six to seven weeks (Tomberlin et al. 2002; Alvarez 2012; Caruso et al. 2013; Dortmans 2015), which according to some authors can be extended by up to four months when unfavorable conditions (food shortage, low temperature, oxygen depletion, drought, etc.) decelerate BSF activity (Furman et al. 1959; Sheppard et al. 1994; Diener 2010; Banks 2014; Tran et al. 2015; Zurbrügg et al. 2018). Five main stages can be distinguished in the BSF's lifecycle: egg, larval, prepupal, pupal and adult (Banks 2014; Oliveira et al. 2015). The larval and pupal stages constitute most of the lifecycle's duration, the egg hatching and adult stages being relatively short in comparison. The larval stage is particularly important as it is the only step of the lifecycle in which the BSF feeds. Therefore, larvae need to store enough fat and protein to sustain their biological activities in the latter stages (Diclaro and Kaufman 2009; Caruso et al. 2013; Dortmans et al. 2017). Figure 1 illustrates the different lifecycle stages of the BSF and its main characteristics.

3. WASTE PROCESSING BY THE BSF

Essentially, waste treatment by the BSF consists of feeding organic waste to BSF larvae to produce energy-rich larvae and organic fertilizer. Several BSF characteristics make this insect particularly attractive for valorizing organic waste:

- The voracious appetite of the BSF larvae for decaying organic matter enables efficient conversion of a wide range of organic waste materials;
- The shortness of the BSF's lifecycle allows its frequent reproduction, therefore ensuring a steady source of larvae to convert the organic waste, as well as a reliable supply of energy-rich larvae that can be used as animal feed;
- The resilience of the BSF facilitates its rearing and makes its use in waste treatment less constraining; and
- Finally, by crawling naturally out of the waste, the prepupae can be easily harvested.

To take advantage of the natural features of the BSF in waste management, its natural lifecycle must be engineered to optimize waste reduction and biomass production. In addition, waste should be treated in a reliable and consistant manner, to stabilize the treatment and production processes and facilitate operations (Zurbrügg et al. 2018). Therefore, this section addresses the technical aspects of the BSF technology, describing how it works and how it can be optimized, based on pilot and/or experimental research literature.

Several aspects should be taken into consideration when siting a BSF processing facility. They include (Zurbrügg et al. 2018):

- Access to utilities (water, electricity);
- Options for wastewater management;
- Existence of an environmental and physical barrier to minimize nuisances (visual or olfactory) to the surrounding environment or intrusion into the premises;
- Secured supplies of quality raw materials; and
- Processing facilities offering suitable growth conditions for the BSF.

The BSF treatment process can be typically disaggregated into: (1) waste preprocessing, (2) BSF breeding, (3) waste treatment, (4) product harvesting, and (5) post-treatment of the products (Dortmans et al. 2017; Zurbrügg et al. 2018). The next section describes the different components of a BSF system and discusses the optimal operating conditions and designs proposed in the literature for each of them (Figure 2).

3.1 Feedstock Selection

3.1.1 Sourcing

The waste received at the treatment facility should be controlled at all times; inorganic and hazardous waste must be removed from the waste stream. Waste nutritive composition is known to play a critical role in BSF activity and growth performance. But many uncertainties remain concerning how the feedstock type and quality could affect the outcome of BSF conversion of waste. Hence, selecting a suitable BSF feedstock has become a complex process, which in many practical cases, is based on waste availability and cost.

FIGURE 1. LIFECYCLE AND CHARACTERISTICS OF THE BSF.

Sources: Based on data provided by Booth and Sheppard 1984; Sheppard et al. 1994; Tomberlin and Sheppard 2002; Diclaro and Kaufman 2009; Diener 2010; Caruso et al. 2013; Banks 2014; Cicková et al. 2015; Dortmans et al. 2017; Lohri et al. 2017; Zurbrügg et al. 2018.

FIGURE 2. THE CONVENTIONAL WASTE TREATMENT PROCESS USING THE BSF.

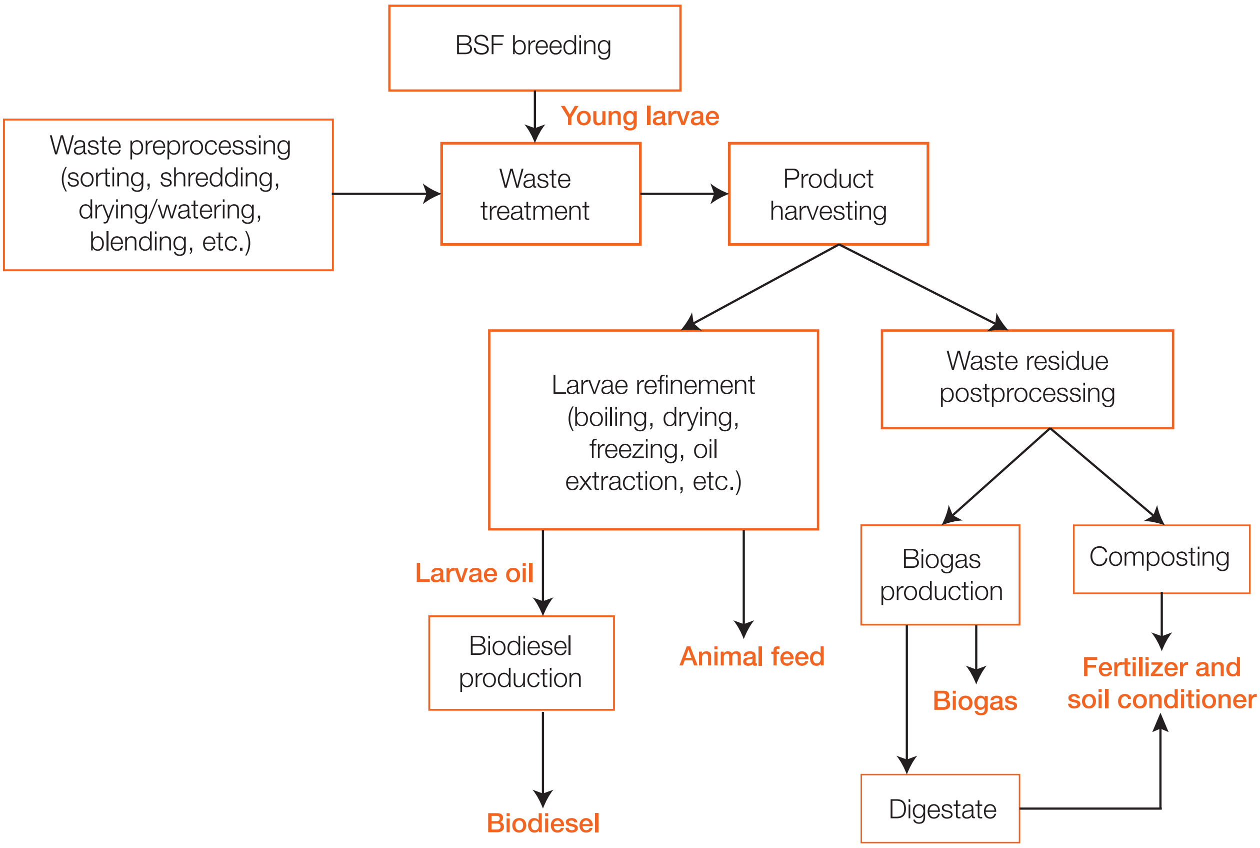


Photo: Gabrielle Joly

In theory, BSF larvae can process a wide range of organic materials due to their powerful mouthparts, the unique composition of their gut microbiota, including bacterial species not found in the microbiota of other insects, as well as the high activity of their digestive enzymes, such as amylase, lipase and protease in their salivary glands and gut (Jeon et al. 2011; Kim et al. 2011; Caruso et al. 2013; Banks 2014). According to the literature, the feedstocks used in the BSF treatment include:

- Mixed municipal organic waste (Diener et al. 2011);
- Food, restaurant and market waste, such as fruit and vegetable waste (Nguyen et al. 2015; Parra Paz et al. 2015; Saragi and Bagastyo 2015; Cheng and Lo 2016; Leong et al. 2016; Lalander et al. 2019);
- Animal manure, such as poultry, cow and pig manure (Sheppard et al. 1994; Yu et al. 2011; Myers et al. 2008; Li et al. 2011b; Newton et al. 2005; Nguyen et al. 2015; Lalander et al. 2019);
- Human feces and fecal sludge (Lalander et al. 2013; Banks et al. 2014; Joly 2018; Lalander et al. 2019); and
- Agroindustrial waste, such as:
    - food processing waste (Lardé 1989; Caruso et al. 2013; Dortmans et al. 2017; Mohd-Noor et al. 2017),
    - spent grains (Dortmans et al. 2017),
    - slaughterhouse waste (Dortmans et al. 2017), and
    - fish waste (Nguyen et al. 2015; Saragi and Bagastyo 2015; St-Hilaire et al. 2007b).

Despite the flexibility of BSF larvae and feedstock, some authors have highlighted key parameters influencing the ability of BSF larvae to process a material (see Table 1). According to Lalander et al. (2019), feedstock could affect three main BSF-related parameters, such as larval development time, the final prepupal weight and the waste-to-biomass conversion rate.

TABLE 1. THE OPTIMAL PARAMETER VALUES FOR FEEDSTOCK.

Parameters pertaining to the feedstock	Optimal values	Suggested preprocessing methods for optimization	References
Nutrient content	Feedstock rich in protein and carbohydrates (e.g. 21% protein and 21% carbohydrate); Suitable C/N ratio: 10-40 (optimal nutrient balance not established). High contents of volatile solids are preferable	Mixing different waste types	St-Hilaire et al. 2007a; Gobbi et al. 2013; Lalander et al. 2015; Cammack and Tomberlin 2017; Dortmans et al. 2017; Lohri et al. 2017; Rehman et al. 2017a, 2017b; Lalander et al. 2019
Fiber content	Not too high (no optimal value established)	Prefermentation	Zheng et al. 2012a; Caruso et al. 2013; Lohri et al. 2017; Mohd-Noor et al. 2017; Rehman et al. 2017a
Moisture content	60-90% (wet weight (WT))	Dewatering, water addition and/or mixing different waste types	Cammack and Tomberlin 2017; Cheng et al. 2017; Dortmans et al. 2017; Lohri et al. 2017
Particle size	1-2 cm	Shredding	Dortmans et al. 2017; Lohri et al. 2017
pH	5-8 (suitable values)	Mixing different waste types	Caruso et al. 2013; Dortmans 2015; Lalander et al. 2015; Rehman et al. 2017a, 2017b
Structure	Sufficient structure to allow the larvae to move through the feedstock, consume it and breathe	Addition of matrix material, such as pine shavings or crushed charcoal	Barry 2004; Perednia 2016

Overall, according to Lalander et al. (2019), protein and total volatile solid contents remain the most critical waste-related factors. Therefore, feedstocks with higher concentrations of these two components should be preferred, such as abattoir waste, food waste and human feces. But pure fruit and vegetable wastes and sewage sludges may not be suitable, unless they are mixed with other acceptable materials. Typically, larval development is favored if the feedstock is rich in protein and easily available carbohydrates (Dortmans et al. 2017; Lalander et al. 2019). When Cammack and Tomberlin (2017) used a balanced diet, i.e. containing 21% protein and 21% carbohydrate, larval development was optimal.

In addition, a suitable C/N ratio is also critical for the biological activity of BSF larvae. Feedstocks with a C/N ratio ranging from 10 to 40 have been reported to be efficiently converted by BSF larvae (Saragi and Bagastyo 2015; Lalander et al. 2015; Rehman et al. 2017a, 2017b). But Rehman et al. (2017b) observed, when comparing different mixtures of dairy manure and soybean curd residue, with C/N ratios ranging from 16.2 to 18.4, that BSF treatment performed best, in terms of fiber reduction and biomass production, for the substrate with a C/N ratio of 16.2. Similarly, Rehman et al. (2017a) recommended a C/N ratio of 14.2 for co-digestion of dairy manure and chicken manure by the BSF. On the other hand, high fat content could be detrimental to BSF growth (Lalander et al. 2019).

3.1.2 Waste Preprocessing

Mixing different types of waste is a preprocessing method that helps to optimize the nutrient balance of the feedstock and could enhance waste reduction, larvae growth and the nutritional content of the larvae (St-Hilaire et al. 2007a; Gobbi et al. 2013; Cammack and Tomberlin 2017; Rehman et al. 2017a, 2017b; Lalander et al. 2019). However, the effects of co-digesting different feedstocks have not yet been fully documented. Other process parameters highlighted in the literature (see Table 1) were moisture content, particle size and nutrient content (Cheng et al. 2017; Dortmans et al. 2017; Lohri et al. 2017).

Lignocellulosic waste, characterized by a high fiber content, such as vegetable waste or dairy manure, has been reported to be harder to convert by the BSF (Zheng et al. 2012a; Lohri et al. 2017; Rehman et al. 2017a, 2017b). Allowing such materials to ferment, so that complex organic molecules are broken down into simpler elements more easily assimilated by BSF larvae, could be a beneficial pretreatment. In the case of waste from oil palm and coconut milk extraction industries, fermentation for typically up to a few weeks is sufficient (Caruso et al. 2013; Mohd-Noor et al. 2017). During a longer fermentation period, too many microorganisms could grow in the substrate and compete with BSF larvae for common nutrients (Mohd-Noor et al. 2017; OVRSol 2010).

The BSF feedstock should be sufficiently moist to allow the larvae to ingest the material. Materials that are too dry cannot be processed by BSF larvae. But if the food source is too wet, the larvae will crawl out of the waste to search for a drier location or their separation from the residue at the end of the treatment will be more difficult (Alvarez 2012; Caruso et al. 2013; Cheng et al. 2017). Alvarez (2012) pointed out that the larvae's development rate can be controlled via the feedstock's moisture content. Latest studies suggested a range of suitable moisture content of approximately 60 to 90% of WW (Cammack and Tomberlin 2017; Cheng et al. 2017; Dortmans et al. 2017; Lohri et al. 2017), while Fatchurochim et al. (1989) reported that moisture contents ranging from 40 to 70% of WW were optimal for BSF larvae development. Therefore, wastes that are too moist, such as fecal sludge or fruit and vegetable waste, may require dewatering before being processed, while water should be added to drier materials such as chicken manure. The ideal solution may be to mix materials of different water content to easily achieve a suitable moisture level (Furman et al. 1959; Dortmans et al. 2017; Lohri et al. 2017).

Regarding particle size, the literature suggests its reduction before processing, for example by using a shredder or a hammer mill (Dortmans et al. 2017; Lohri et al. 2017). Feedstocks with particle size smaller than 1 to 2 centimeters (cm) in diameter allow the larvae, which have no chewing mouthparts, to access food more easily (Dortmans et al. 2017). Another important parameter, though rarely addressed in the literature, is the structure of the feedstock. Barry (2004) and Perednia (2016) highlighted the importance of ensuring that the feedstock has enough structure to allow the larvae to move through the material, consume it and obtain an adequate supply of oxygen. Perednia (2016) recommended adding matrix materials, such as pine shavings and crushed charcoal, to improve the ability of BSF larvae to burrow and move through the waste pile.

The literature does not identify pH as a key factor that influences the ability of BSF larvae to process a feedstock, and none of the studies reviewed proposes an optimal range for pH value. Feedstocks with pH ranging from 5 to 8 have been processed successfully in experiments involving BSF larvae (Caruso et al. 2013; Dortmans 2015; Lalander et al. 2015; Rehman et al. 2017a). However, Rehman et al. (2017b) reported that buffer capacity is crucial for the biological activity of BSF larvae. Comparing BSF treatment performance for different mixtures of dairy manure and soybean curd residue, whose pH ranged from 5.1 to 7.9, Rehman et al. (2017b) observed the greatest fiber reduction and biomass production for the substrate exhibiting a pH of 6.7, while a pH of 7.8 was recommended by Rehman et al. (2017a) for co-digesting dairy and chicken manures with the BSF.

3.2 Breeding Conditions

Two main types of BSF waste treatment systems can be distinguished, namely systems relying on natural colonization by the BSF and artificial breeding systems (Cicková et al. 2015; Lohri et al. 2017). Systems relying on natural colonization are mainly used at the household level, typically for backyard applications (Lohri et al. 2017). They are unsuitable in the context of a controlled waste treatment facility (Cicková et al. 2015; Lohri et al. 2017). Therefore, recent literature mostly focuses on artificial breeding systems, which include a breeding unit where the BSF are bred in captivity to produce young larvae (Diener et al. 2015a; Lohri et al. 2017; Dortmans et al. 2017). Such systems are more expensive and complex than those depending on natural BSF populations but allow for a controlled operation and stable production (Cicková et al. 2015; Lohri et al. 2017). Therefore, the present review focuses on the latter system.

Diener et al. (2015a) and Lohri et al. (2017) highlighted the key role played by the breeding unit in a BSF waste treatment facility as the production of enough young larvae is crucial to ensure the running of the waste treatment process. They also pointed out that maintaining a large enough and healthy BSF colony is the most delicate step of the process (Diener et al. 2015a; Lohri et al. 2017). To maintain the colony, a fraction of the young larvae is typically kept in the breeding unit or, alternatively, prepupae harvested from the waste treatment unit are reintroduced in the breeding unit to pupate into flies (Nature 2016; Dortmans et al. 2017). Flies are then used to produce eggs, which are incubated until they hatch into larvae. The optimal operating conditions and designs to rear the BSF at each stage of its lifecycle are discussed in the following sections and summarized in Table 2.

Photo: Gabrielle Joly

TABLE 2. OPTIMAL BREEDING CONDITIONS AND OPERATIONAL DESIGNS SUGGESTED IN THE LITERATURE.

	Optimal operating conditions					Suggested	References
Lifecycle stage	Temperature	Humidity	Light	Diet	Other	operational designs	
Eggs	Constant temperature (e.g. ~ 27 °C)	> 60%	Dark environment, with 0-50% daily light exposure	None	-	Eggs incubated in a covered container and placed above a feed source for neonate larvae	Sheppard et al. 2002; Zhang et al. 2010; Diener et al. 2011; Alvarez 2012; Holmes et al. 2012, 2017; Mutafela 2015
Juvenile larvae (4-6 days old)	Constant temperature in the 24-33 °C range	Relatively constant humidity level	Dark environment	Special diet (e.g. wheat bran, rabbit or chicken feed) with enough structure	-	Juvenile larvae kept for 4-6 days after hatching in the incubation container	Sheppard et al. 2002; Diener et al. 2011; Caruso et al. 2013; Dortmans et al. 2017; Yang 2017
Larvae	24-33 °C	The literature focuses on the moisture content of the feedstock	Dark environment	Well-defined diet or organic waste to be treated	-	Larvae fed with a well-defined feed until they reach the prepupal stage or are used for waste treatment	Sheppard et al. 2002; Tomberlin et al. 2002; Alvarez 2012; Caruso et al. 2013; Harnden and Tomberlin 2016; Dortmans et al. 2017
Prepupae/pupae	In the same range as the larval stage (24-33 °C)	60-70%	Dark environment, with 0-50% daily light exposure	None	Pupation medium (e.g. wood chips, coco peat, compost) exhibiting a moisture level of 50-85% and a depth of 15-20 cm	Prepupae collected in a container filled with a dry and water-absorbing material, connected to the feeding container through a pipe (inclination: 28-45°) or feeding container placed directly in the collection container	Newton et al. 2005; Diener et al. 2011; Alvarez 2012; Caruso et al. 2013; Banks 2014; Mutafela 2015; Lin 2016; Nakamura et al. 2016; Dortmans et al. 2017; Holmes et al. 2017
Adults	25-32 °C	> 60%	Morning sunlight	None, but providing water with sugar is recommended	Sufficient space to mate in flight. High fly density (5,000 flies m^{-3}). Plant to favor lekking.	Greenhouse or netted cage (size ranging from 0.27 x 0.27 x 0.27 meters (m) to 3 x 3 x 6 m). Oviposition media with cavities made of cardboard or wood and placed on or close to organic matter with a sufficiently strong smell	Booth and Sheppard 1984; Holmes et al. 2012; Sheppard et al. 2002; Tomberlin and Sheppard 2002; Zhang et al. 2010; Diener et al. 2011; Alvarez 2012; Caruso et al. 2013; Mutafela 2015; Nakamura et al. 2016; Dortmans et al. 2017

3.2.1 Mating and Oviposition

About two days after emerging, BSF mate whilst in fly through lekking, a mating behavior characterized by the clustering of males in a given location and attraction of females through competitive display (Tomberlin and Sheppard 2001; Diclaro and Kaufman 2009; Furman et al. 1959; Diener 2010; Caruso et al. 2013). Then, about two days after mating, females extend their ovipositor to lay their eggs in the form of a single clutch (Tomberlin and Sheppard 2002; Cicková et al. 2015). In general, the number of eggs laid by each BSF female ranges from 320 to 1,000 (Tomberlin et al. 2002; Diclaro and Kaufman 2009; Caruso et al. 2013; Banks 2014; Dortmans et al. 2017). The adult fly dies once its fat reserve is depleted (Alvarez 2012; Myers et al. 2008), i.e., typically a few hours after oviposition for females (Tomberlin et al. 2002).

Oviposition usually takes place close to decaying organic matter so that, immediately after hatching, the larvae have access to a feed source. In addition, for oviposition, female flies seem to choose media that have small cavities into which they can lay their egg packages to ensure their protection from predators and prevent their dehydration by direct sunlight (Caruso et al. 2013; Dortmans et al. 2017). The eggs hatch after about three to four days (Sheppard et al. 2002; Diclaro and Kaufman 2009; Dortmans et al. 2017).

Operating Conditions

Three main environmental parameters influence mating and oviposition of the BSF, namely temperature, light and humidity. Temperature plays an important role in ensuring mating and oviposition (Tomberlin and Sheppard 2002; Alvarez 2012).

BSF females require temperatures greater than 26 °C to lay eggs (Tomberlin and Sheppard 2002). Booth and Sheppard (1984) in particular observed that 99.6% of oviposition took place when temperatures were between 27.5 and 37.5 °C. Dortmans et al. (2017) recommended an optimal range of 25 to 32 °C to rear adult BSF.

Tomberlin and Sheppard (2002) established that high light intensity promotes mating. Specifically, they observed that, under sunlight, most mating (75%) occurred when light intensity was greater than 200 µmol m^{-2} s^{-1} and a minimum light intensity of 63 µmol m^{-2} s^{-1} was required for mating to take place. But Zhang et al. (2010) recorded that over 110 µmol m^{-2} s^{-1}, the mating activity of flies exposed to sunlight decreased. This difference could be because, in addition to light intensity, the time of day has been shown to influence the mating rate. Mating occurs generally early in the day (with a peak at 10:00), while oviposition generally takes place later in the day (Tomberlin and Sheppard 2002; Zhang et al. 2010). Some authors report that light source and wavelength range also influence mating activity. In particular, mating is stimulated by sunlight, as well as artificial light with wavelengths from 450 to 700 nanometers (nm). However, greater fertility and hatchability may be achieved with sunlight than with artificial light (Tomberlin and Sheppard 2002; Zhang et al. 2010; Nakamura et al. 2016).

On the other hand, light does not seem to influence oviposition. Under unsuitable light conditions, BSF females could lay eggs without having mated. However, these eggs are infertile (Tomberlin and Sheppard 2002). In addition, Zhang et al. (2010) recorded similar numbers of eggs laid under sunlight and light from a quartz-iodine lamp with a 350 to 2,500 nm spectrum. Moreover, the light source used to stimulate mating does not seem to affect larval development and pupation later because Zhang et al. (2010) observed similar larval and pupal development times with the quartz-iodine lamp and natural sunlight.

Furthermore, it appears that humid conditions could prolong the lifespan of BSF adults and thus promote their reproduction (Caruso et al. 2013). Typically, adults reared under a 70% relative humidity level live two to three day longer than those in drier environments (Holmes et al. 2012). Similarly, providing water for the flies to drink is also reported to be beneficial because flies provided with water live one to two days longer than those without water (Tomberlin et al. 2002). Adding sugar to the water is also reported to promote reproduction (Caruso et al. 2013; Nakamura et al. 2016). Humidity may also have an influence on oviposition as Tomberlin and Sheppard (2002) reported that 80% of eggs are laid when humidity exceeds 60%. However, Sheppard et al. (2002) observed mating and oviposition in a range of humidity conditions as wide as 30 to 90%.

To choose an oviposition site, females use the tip of their abdomen, which contains the ovipositor, i.e. the body part used to lay eggs, which is covered by sensors. Therefore, when searching for an oviposition site, BSF females drag the tip of their abdomens along the surface of a substrate to probe its characteristics. This process gives females information about the presence of BSF eggs, larvae, competitors or pathogens in the substrate, as well as the availability of nutrients (Tomberlin 2017). Zheng et al. (2013a) observed that ovipositing females were attracted by substrates containing bacteria isolated from BSF eggs, while they were generally repelled by the presence of bacteria isolated from competing insects, such as blow flies or beetle larvae. Females, in search of an oviposition site, may also be attracted by the effluent from decomposing waste and leave chemical markers to attract other females to the laying site (Sheppard et al. 2002; Alvarez 2012).

Operational Designs

For the mating unit, different designs can be found in the literature. The most widespread are greenhouses (Sheppard et al. 2002; Diener et al. 2011; Alvarez 2012; Caruso et al. 2013) and netted cages (Zhang et al. 2010; Mutafela 2015; Popoff and Maquart 2016a; Dortmans et al. 2017; C. Lalander, pers. comm., June 16, 2017). Depending on the availability of sunlight, mating units are either equipped with lamps (Mutafela 2015) or exposed to sunlight (Diener et al. 2009b; Alvarez 2012; Popoff and Maquart 2016a). However, in tropical regions, it is recommended not to place the cage in direct sunlight to avoid the rapid dehydration of the flies (B. Dortmans, pers. comm., September 28, 2017). The mating unit has to be big enough to allow the flies to mate in flight (Barry 2004; Alvarez 2012; Caruso et al. 2013; Banks 2014). Sizes reported in the literature for the mating cage typically range from 0.7 x 0.7 x 1.4 m to 3 x 3 x 6 m (Sheppard et al. 2002; Tomberlin and Sheppard 2002; Zhang et al. 2010; Diener et al. 2011; Charlton et al. 2015; Mutafela 2015; Dortmans et al. 2017), with fly density ranging from about 100 up to 5,200 flies m^{-3} (Tomberlin and Sheppard 2002; Zhang et al. 2010; Charlton et al. 2015). Caruso et al. (2013) recommended that the ceiling of the mating cage should be higher than 1.5 m, as Tomberlin and Sheppard (2001) observed that in nature BSF couples can fly up to 1.5 m above the ground while mating. However, Nakamura et al. (2016) showed that fertilized eggs could be obtained in a cage as small as 27 x 27 x 27 cm with a high fly density (5,000 flies m^{-3}). In addition, several authors, based on the observations of Tomberlin and Sheppard (2001), suggested placing plants, either natural or artificial, in the mating unit to favor lekking and thus mating (Caruso et al. 2013; Mutafela 2015). In addition, plants provide sites for flies to rest on (Cicková et al. 2015). In several set-ups, the flies are also kept hydrated by regularly spraying them with water and/or by placing a wet cloth on a container filled with water or wet cotton so that the flies do not drown in it (Alvarez 2012; Caruso et al. 2013; Popoff and Maquart 2016a; Dortmans et al. 2017).

Alvarez (2012) and Dortmans et al. (2017) highlighted the importance of providing a suitable medium for oviposition so that all females lay their eggs in the same location, thus facilitating egg harvesting. The oviposition medium needs to fulfil several conditions. Booth and Sheppard (1984) observed that BSF females prefer to lay their eggs on dry media. In the literature, several designs with different materials and shapes are proposed for the oviposition medium. Cardboard and wood are the most widely used materials (Booth and Sheppard 1984; Diener et al. 2011; Tomberlin et al. 2002; Mutafela 2015). Other materials include paper towels (Nakamura et al. 2016) or dry banana tree leaves (Caruso et al. 2013; Popoff and Maquart 2016a). Examples of designs include strips of cardboard or wood tied together so that they are separated by small gaps (Mutafela 2015; Dortmans et al. 2017), cardboard honeycomb (Dortmans et al. 2017; C. Lalander, pers. comm., June 16, 2017), cardboard rolls (Zhang et al. 2010), blocks made of three layers of corrugated cardboard glued together (Sheppard et al. 2002; Tomberlin et al. 2002) and strips of corrugated cardboard wrapped around skewers and tucked into rings of bamboo (Diener et al. 2011). Dortmans et al. (2017) also suggested using ‘bioballs’, normally designed as biofilters for aquariums of fish ponds.

In addition, the oviposition medium should preferably be placed on or close to organic matter with a sufficiently strong smell to attract females to lay their eggs into the oviposition medium. In most experimental settings, decomposing organic waste is used (Dierner et al. 2011; Mutafela 2015). Dortmans et al. (2017) suggested that dead flies and eggs themselves could be used as an attractant and thus recommended mixing the fresh attractant substrate with the residue from an old container used to collect eggs, which is also suggested by Tomberlin (2017). On the other hand, Furman et al. (1959) and Tomberlin (2017) suggested that females are more attracted to substrates already containing BSF larvae and thus recommended placing larvae in the attractant container, but other authors did not back this hypothesis (Kemppineen 1998; Tomberlin and Sheppard 2002). Mutafela (2015) also pointed out that the attractant should not be too wet to prevent females from drowning in it. Finally, Dortmans (2015) reported that female flies prefer shaded sites, perceived as safer, to lay their eggs. Therefore, Dortmans et al. (2017) proposed placing a shading basket above the oviposition medium.

3.2.2 Egg Harvesting and Hatching

Operating Conditions

According to Alvarez (2012), eggs are particularly vulnerable to changes in environmental parameters. Therefore, eggs should preferably be held at a constant temperature until hatching. For example, Sheppard et al. (2002) reported that keeping eggs at 27°C yields satisfactory results as they observed egg-hatching rates exceeding 80% under sufficient humidity. Regarding humidity, Holmes et al. (2012) reported that egg-hatching success increases as the relative humidity level increases. More precisely, they reported that humidity levels of more than 60% result in optimal egg-hatching rates and prevent desiccation of the eggs (Holmes et al. 2012).

Operational Designs

In all the designs proposed in the literature reviewed, oviposition media containing eggs are harvested and transferred to another location for hatching. The oviposition media are usually placed above (Dortmans et al. 2017) or directly on a high-quality feed source adapted to the newly hatched larvae (Zhang et al. 2010; Diener et al. 2011; Mutafela 2015). In a few cases, eggs clusters are removed manually from the oviposition medium and placed directly in a hatching container. However, this method is labor-intensive and therefore, not recommended for large-scale operations (Caruso et al. 2013; Popoff and Maquart 2016a). The hatching container is usually covered, for example, with a fine mesh to protect the eggs and the juvenile larvae from predators (Sheppard et al. 2002; Zhang et al. 2010; Diener et al. 2011; Mutafela 2015; Nakamura et al. 2016; Popoff and Maquart 2016a). In the study led by Diener et al.

(2011), the hatching containers were placed in a dark and warm environment; however this is not in line with findings by Holmes et al. (2017) who found that eggs hatched faster when they are exposed to 12 hours of light day^{-1} than if they are exposed to 0 or 8 hours of light day^{-1} (2012).

3.2.3 Larvae Breeding

Newly hatched larvae are particularly sensitive to changes in environmental conditions and food competition. Therefore, feeding them with a special diet and keeping them in a controlled and protected environment for a few days, typically four to six days, increases their survival rate (Diener et al. 2011; Popoff and Maquart 2016a; Dortmans et al. 2017; C. Lalander, pers. comm., June 16, 2017). Various diets for the young larvae are suggested in the literature. They include a mixture of corn meal, wheat bran and water (Mutafela 2015 adapted from Sheppard et al. 2002), rabbit feed mixed with water (Diener et al. 2011) or chicken feed for starter chicks mixed with water (Dortmans et al. 2017). Yang (2017) indicated that the lack of structure of the feed source is particularly problematic for juvenile larvae which are not strong enough to create pore space to breathe. They advised against using diets characterized by too-fine particle size, such as alfalfa and corn meal, or that are too sticky, like cooked sorghum. Instead, it is recommended to add matrix materials that have low density but high rigidity, such as wood branches, wheat bran, rice bran or wood-shaving dust to the diet in order to create a loose texture that will allow the juveniles to breathe (C. Lalander, pers. comm., June 16, 2017; Yang 2017).

In the literature, two main scenarios are encountered regarding the fate of four-to-six day-old larvae. In the first, a fraction of the young larvae is kept in the breeding unit to reach the adult stage and hence produce new larvae (Popoff and Maquart 2016a; Dortmans et al. 2017). Another option is using all the larvae in the treatment process but later on reintroducing a fraction of the prepupae into the breeding unit so that they pupate and emerge as adult flies (Newton et al. 2005; Caruso et al. 2013; Nature 2016). In the first scenario, the larvae kept in the breeding unit are placed into a container filled with a well-defined feed until they reach the prepupal stage (Dortmans et al. 2017; Zurbrügg et al. 2018). An example of artificial diet, recommended by Sheppard et al. (2002) and Tomberlin et al. (2002) for breeding BSF larvae, is the Gainseville diet, which consists of 50% wheat bran, 30% alfalfa meal and 20% corn meal. In the second scenario, there is a risk that the colony could collapse in the case of system failure, for instance if the waste is contaminated. On the other hand, feeding the larvae with a controlled diet, despite being more expensive, reduces the risk of failure. In addition, as diet has been shown to influence both the physiological and morphological characteristics of the adult fly, and especially female fertility, controlling the larval diet maintains a healthy and productive colony (Gobbi et al. 2013).

Some authors reported that larvae are photophobic and should therefore be held in a dark environment (Caruso et al. 2013; B. Dortmans, pers. comm., September 28, 2017). However, a recent study by Holmes et al. (2017) established that if the larvae are kept in the dark, they require about one-third more time to develop into adults. Ideal temperature for larval development ranges between 24 and 33 °C (Alvarez 2012; Dortmans et al. 2017). If the temperature is too high in the waste, the larvae will crawl out of the food source to find a cooler location. On the other hand, larvae subjected to low temperatures will slow down their metabolisms to survive, which means that they will feed less and thus grow at a slower pace (Dortmans et al. 2017). Because larvae generate heat by moving into the food source as they feed, Alvarez (2012) suggested that larvae better withstand temperatures which are lower compared to the optimal range than higher temperatures.

The temperature at which the larvae are reared, besides influencing the larval growth rate, also affects the size and lifespan of the future adult fly. Tomberlin et al. (2009) reported that, above 27 °C, as the temperature increases smaller adults with shorter lifespan are observed. In addition, between 27 °C and 30 °C, they observed trade-offs between the larval development time (the larvae take less time to reach maturity as the temperature increases), the adult lifespan (adults live for a shorter time when the development temperature is higher) and the prepupal weight (prepupae are heavier at lower temperatures). On the other hand, Harnden and Tomberlin (2016) observed that larvae reared at 24.9 °C reached maturity faster but their final weight was on average 30% lower than larvae reared at 27.6 °C and 32.2 °C, which suggests that below ~ 27 °C, the trend is reversed. Furthermore, Tomberlin et al. (2009) observed that only 0.1% of larvae reared at 36°C reached the adult stage, which suggests that sustained high temperatures are not suitable for breeding larvae. Based on these studies, the upper temperature limit seems to lie between 33 and 36 °C (Tomberlin et al. 2009; Harnden and Tomberlin 2016).

3.2.4 Collection of Migrating Prepupae

When the larvae attain the prepupal stage, they have reached their maximum size. They stop feeding and empty their digestive tracts (Diener 2010; Banks 2014; Dortmans et al. 2017). Using their hook-shaped mouthparts, they emerge from the food source and reach a dry, dark and protected location to pupate into adult flies (Diener 2010; B. Dortmans, pers. comm., September 28, 2017). The average time of migration is not reported in the literature. According to Alvarez (2012), this depends on the larvae's ability to find a suitable pupation site. Alvarez (2012) also suggested that larvae may leave a chemical trail during their search for a pupation site for other larvae to find, resulting in a migration path.

To contain the prepupae that crawl out of the feed source, the feeding container must be connected to another container filled with a dry and water-absorbing material (Dortmans et al. 2017). This latter container can either be used directly as a pupation container (Diener et al. 2011; Mutafela 2015) or as a transfer container (Dortmans et al. 2017). Regarding the connection between the two containers, ramps connected to a pipe leading to the pupation container can be used (Diener et al. 2011; Mutafela 2015). For the exit ramp, inclinations ranging from 28° to 45° have been successfully tested (Newton et al. 2005; Diener et al. 2011; Banks 2014; Mutafela 2015). However, Banks (2014) reported that BSF prepupae can climb up vertical surfaces if the moisture is sufficient to maintain surface tension. Therefore, instead of using ramps to connect the feeding container to the collection container, the feeding container can be placed directly into the collection container in which the prepupae will fall once they have climbed up the internal wall of the feeding container (Nakamura et al. 2016; Dortmans et al. 2017).

3.2.5 Pupation

Pupation is reportedly favored by stable temperature conditions, in the same range as the larval stage (Dortmans et al. 2017). However, the impact of light is somewhat unclear. While some authors assert that pupae are photophobic and require a dark environment (B. Dortmans, pers. comm., September 28, 2017; Caruso et al. 2013), a recent study by Holmes et al. (2017) established that pupae exposed to light 12 hours day^{-1} emerged faster as adults compared to pupae held in the dark. Adult emergence success seems to increase with rising relative humidity levels. Typically, a humidity level of 60 to 70% is recommended as it prevents the desiccation of pupae (Alvarez 2012; Holmes et al. 2012).

Various materials have been proposed in the literature as pupation medium. Some authors suggested dry materials, such as wood chips (Diener et al. 2009b, 2011; Alvarez 2012), hay (Diener et al. 2011), peat (Mutafela 2015), dried coffee grounds (Nakamura et al. 2016) and even pieces of empty arboreal termites' nests (Diener et al. 2011). On the other hand, Dortmans et al. (2017) recommended using a moist material such as compost, moist coco peat or pot soil, into which the pupae can bury. This is supported by Lin (2016), who found that optimum adult emergence rates are obtained by maintaining a moisture level of 50 to 85% in the pupation medium. Finally, Alvarez (2012) recommended providing a pupation medium at a depth of between 15 and 20 cm.

To prevent the emerging flies from escaping, Diener et al. (2011) reported using a nylon net, while Dortmans et al. (2017) recommended placing the pupation containers inside a dark cage, which, in addition to containing the newly emerged flies, provides stable environmental conditions, favoring the pupation process. Regarding the location of the pupation container, two main options are described in the literature. The first consists of placing the pupation container directly in the mating cage (Mutafela 2015) so that when the flies emerge from the pupation shell, they can directly mate. However, in most set-ups, pupation occurs in sealed containers and once the flies have emerged, they are released into the mating cage (Diener et al. 2011; Popoff and Maquart 2016a; Dortmans et al. 2017).

3.2.6 Monitoring of Breeding Performance

Dortmans et al. (2017) recommended monitoring survival rates at every stage of the BSF lifecycle, as well as the oviposition rate in order to assess the performance of the breeding process and identify potential problems. Table 3 compares values, for commonly used breeding performance indicators, recorded in two Indonesian BSF waste treatment facilities.

TABLE 3. COMPARISON OF BREEDING PERFORMANCE IN TWO INDONESIAN FACILITIES.

Performance indicators	Values (%) reported by Dortmans et al. (2017)	Values (%) reported by Caruso et al. (2013)
Hatching rate	70	80
Larval survival rate	70	60
Adult emergence rate	80	90
Oviposition rate	350 eggs female^{-1}	18 eggs female^{-1} [a]

[a] Calculated based on the value provided by Dortmans et al. (2017) for the average weight of an egg (25 µg). As pointed out by Caruso et al. (2013), this value is very low compared to values reported in the literature, which could be explained by a range of physical, behavioral, abiotic or technical factors.

3.3 Waste Treatment

The waste treatment itself consists of feeding the young larvae produced in the breeding unit with the organic waste to be processed. The larvae fed on the waste grow into energy-rich prepupae while reducing the waste (Dortmans et al. 2017). Compared to breeding, the waste treatment step is relatively simple (Lohri et al. 2017). Optimal operating conditions for BSF waste treatment are summarized in Table 4, while the main operational designs proposed in the literature for BSF rearing containers are described in Table 5.

TABLE 4. OPTIMAL OPERATING CONDITIONS FOR BSF WASTE TREATMENT.

Operating parameter	Optimal value	References
Feeding rate	20-130 for high biomass production and 4-60 for high reduction rate (mg [milligram] larva^{-1} day^{-1}, dry weight [DW]), depending on the waste type	Myers et al. 2008; Diener et al. 2009b; Caruso et al. 2013; Banks 2014; Parra Paz et al. 2015
Larval density	1.2-5 larvae cm^{-2}	Parra Paz et al. 2015
Waste layer thickness	< 7.5 cm or < 15 cm if matrix materials are added to the waste	Perednia 2016; Yang 2017

TABLE 5. OPERATIONAL DESIGNS PROPOSED IN THE LITERATURE FOR THE BSF REARING CONTAINERS.

	Characteristics	References
Type	Individual containers or larger basins	Tomberlin et al. 2002; Newton et al. 2005; Diener et al. 2011; Caruso et al. 2013; Devic 2014; Charlton et al. 2015; Lalander et al. 2015; Mutafela 2015; Popoff and Maquart 2016a, 2016b; Dortmans et al. 2017
Volume	40-400 liters (L)	
Material	Plastic, metal or concrete	
Special features	Drainage system, system to prevent disturbance from other insects or predators	

3.3.1 Operating Conditions

Optimal environmental conditions and diet for BSF larvae have been discussed in Sections 3.1 and 3.2.3. Additional key operating conditions for waste treatment are larval density, feeding rate and the feeding regime. When choosing an appropriate feeding rate and larval density, there is a trade-off between waste reduction efficiency (waste management perspective), promoted by a low feeding rate and high larval density, and biomass production (economic perspective), favored by a high feeding rate and low larval density (Diener et al. 2009b; Parra Paz et al. 2015; Manurung et al. 2016). In addition, Dortmans et al. (2017) pointed out that if the feeding rate is too high, BSF larvae are not able to process all the waste, resulting in an unprocessed waste layer, where heat can build up due to bacterial activity, creating an unfavorable environment for the larvae. On the other hand, a feeding rate that is too low results in food shortage, which hinders larval development and waste treatment efficiency (Dortmans et al. 2017). Table 6 presents optimal feeding rate values for different feedstocks in terms of larval growth, waste reduction and both parameters.

TABLE 6. OPTIMAL FEEDING RATE VALUES IN TERMS OF BIOMASS PRODUCTION AND/OR WASTE REDUCTION FOR DIFFERENT FEEDSTOCKS.

Feedstock	Optimal feeding rate (mg larva^{-1} day^{-1}) in terms of…			References
	…biomass production	…waste reduction	…both biomass production and waste reduction	
Chicken feed (UFA 625) (60% moisture content)	$\geq 200^a$	100^c	100	Diener et al. 2009b
Vegetable and fruit waste (DW)	$\geq 130^a$	$\leq 20^b$	163^d	Parra Paz et al. 2015; Saragi and Bagastyo 2015
Dairy manure (~ 70% moisture content)	$\geq 70^a$	$\leq 27^b$	-	Myers et al. 2008
Human feces (65-85% moisture content)	$\geq 200^a$	$\leq 50^b$	-	Banks 2014
Palm kernel meal (DW)	$\geq 64^a$	$\leq 4^b$	-	Caruso et al. 2013

Note: [a] ≥ indicates that it was the maximal value tested in the experiment; [b] ≤ indicates that it was the minimal value tested in the experiment; [c] this value was established using the waste reduction index, which in addition to taking into account the waste reduction, considered the larval development time; [d] this value was established using additional parameters, besides biomass production and waste reduction, i.e. the temperature change, the final pH and the leachate production rate.

Besides the influence of feeding rate on bioconversion performance, Parra Paz et al. (2015) also showed that larval density was a key parameter that had an even greater impact than the feeding rate. Studying vegetable and fruit waste, they suggested an optimal larval density of 1.2 larvae cm^{-2}. They established however that high biomass production could be achieved with a larval density as high as 5 larvae cm^{-2} as long as the feeding rate was below 95 mg larva^{-1} day^{-1} (DW). Indeed, they observed that using both high larval density (over 5 larvae cm^{-2}) and a high feeding rate (over 95 mg larva^{-1} day^{-1}, DW) reduces the performance of the system in terms of both waste reduction and larval growth. In addition, it results in increased acidity, temperatures and leachate production (Parra Paz et al. 2015).

Another important aspect to consider is the feeding regime. First, a choice has to be made between continuous and batch regimes. In a continuous system, larvae and waste are added continuously to a container, which is emptied only when it is full. On the other hand, in a batch operation, a defined amount of waste and number of larvae are added to a container, which is harvested when the larvae have reached maturity (Dortmans et al. 2017). By comparing batch and continuous operations, Mutafela (2015) observed better performances, in terms of waste reduction, prepupal weight and larval development time, for the batch mode. Alvarez (2012) and Dortmans et al. (2017) also recommended operating a BSF system in the batch mode to simplify maintenance of the system and isolate risks such as diseases to avoid whole system failure. Furthermore, within the batch mode, several feeding regimes can be distinguished. Banks et al. (2014) compared incremental feeding, where larvae were fed every two days with fresh feces, and lump amount feeding, consisting of providing larvae with one sample of human feces at the beginning of the feeding period. Lump amount feeding yielded better results in terms of larval growth but resulted in longer development time compared to incremental feeding, while waste reduction efficiency was similar between the two feeding regimes (Banks et al. 2014).

The thickness of the waste layer is another important operational parameter, as it affects the ability of larvae to obtain a sufficient supply of oxygen. If the waste layer is too thick, larvae that tend to dig down without stopping will die of lack of oxygen as they get too deep into the waste pile. In addition, the bottom layer of the waste pile, where the larvae cannot live because of anaerobic conditions, will remain unprocessed by the larvae. In this regard, Dortmans et al. (2017) suggested that the waste layer should not exceed 5 cm thickness, while Perednia (2016) and Yang (2017) recommended a maximal depth of about 7.5 cm for the feedstock. As pointed out by Cicková et al. (2015), the waste layer thickness significantly limits the volume of waste that can be processed per square meter in a BSF facility, and implies greater space requirement, or using many shallow trays or basins, resulting potentially in a more labor-intensive process. However, Perednia (2016) reported that using matrix materials, such as pine shavings or crushed charcoal, improves the ability of BSF larvae to move through the waste pile and thus aerate it, which allows, at air pressure of about 100 hPa, to at least double the maximum depth at which oxygen supply is sufficient for the larvae to live, from about 7.5 cm to 15 cm. This allows, in turn, to at least double the waste-processing capacity per square meter. In addition, Perednia (2016) suggested mixing, turning or pumping air through the waste pile in order to ensure optimal oxygen supply for the larvae.

Furthermore, some authors have explored the use of microorganisms to optimize bioconversion by the BSF. Dortmans et al. (2017) suggested the potential role of symbiotic microorganisms, which make nutrients available, through the degradation of cell structures, for the larvae to assimilate them. Yu et al. (2011) investigated the effect of inoculating poultry manure with companion bacteria (*B. subtilis* strains S15, S16, S19 and B. natto strain D1) on larval development. They reported that adding these four strains of *Bacillus subtilis* to the substrate enhanced larval development, as larger larvae were produced in a shorter time (Yu et al. 2011). Findings reported by Yu et al. (2011) are supported by a study conducted by Zheng et al. (2012a), who tested the co-conversion of rice straw and restaurant waste by the BSF and microbes (Rid-X). They reported that associating BSF with Rid-X microbes enhanced conversion of cellulose and hemicellulose into sugar, which was used by the BSF for development, as well as lignin degradation. In addition, by making more nutrients available, Rid-X microbes promoted nutrient utilization by BSF larvae and the incorporation of these nutrients into their biomass, resulting in greater biomass production. Protein utilization by the BSF increased from 74 to 92% by adding Rid-X microbes to the substrate. Zheng et al. (2012a) particularly recommended the use of microorganisms to assist the BSF in the conversion of lignocellulosic materials, which the BSF have more difficulty in processing.

3.3.2 Operational Designs

In the treatment unit, the waste to be processed is typically placed in containers where the small larvae from the breeding unit are added to quickstart the waste decomposition process. As reported in the literature, these are usually made of plastic (Tomberlin et al. 2002; Lalander et al. 2015; Mutafela 2015; Dortmans et al. 2017), metal (Diener et al. 2011; Devic 2014) or concrete (Newton et al. 2005; Caruso et al. 2013; Popoff and Maquart 2016a, 2016b). Containers with a wide range of volumes, i.e. from 40 to 400 L, are reported in the literature (Diener et al. 2011; Caruso et al. 2013; Lalander et al. 2015; Charlton et al. 2015; Mutafela 2015; Popoff and Maquart 2016b; Dortmans et al. 2017). They consist typically of either individual containers that can be handled by operators (Diener et al. 2011; Lalander et al. 2015; Dortmans et al. 2017) or larger basins (Newton et al. 2005; Caruso et al. 2013; Popoff and Maquart 2016a, 2016b). However, Dortmans et al. (2017) recommended avoiding very large containers so that risk is divided in the event of a problem. In addition, to save space, several authors suggest taking advantage of vertical space by stacking individual containers upon each other with ventilation frames in-between levels to allow air to flow or placing them on vertical shelves (Popoff and Maquart 2016a, 2016b; Dortmans et al. 2017; Zurbrügg et al. 2018). Most containers are rectangular in shape, however Caruso et al. (2013) described an Indonesian BSF facility that uses circular basins. Additionally, some authors reported fitting the containers with a drainage system, usually consisting of a plastic pipe leading to a tap, in order to prevent liquid from stagnating and creating anaerobic conditions (Diener et al. 2011; Mutafela 2015).

The literature also describes various systems to prevent the invasion of insects, like wasps or flies, or predators such as lizards, which can disturb the process. To trap other insects, authors have suggested using buckets (Diener et al. 2009b; Dortmans et al. 2017) or building a concrete channel that surrounds the facility (Popoff and Maquart 2016b). Filling them with water and a few drops of liquid detergent or oil enables the reduction of water surface tension and thus drowning of insects (Diener et al. 2009b; Popoff and Maquart 2016b; Dortmans et al. 2017). Popoff and Maquart (2016b) also suggested using double-door systems to isolate the waste treatment unit.

3.3.3 Monitoring of the Waste Treatment Unit's Performance

Common parameters used in the literature to assess the system's performance are waste reduction rate (Diener et al. 2009b, 2011; Banks et al. 2014; Lalander et al. 2015; Dortmans et al. 2017; Lohri et al. 2017; Lalander et al. 2019), bioconversion rate (Banks et al. 2014; Lalander et al. 2015; Lohri et al. 2017; Dortmans et al. 2017; Lalander et al. 2019), mean larval/prepupal weight (Cicková et al. 2015; Lalander et al. 2019), larval development time (Diener et al. 2009b; Cicková et al. 2015; Lohri et al. 2017) and feed/food conversion rate (FCR) (Diener et al. 2011; Caruso et al. 2013; Banks et al. 2014). As the performance of a BSF system depends on the type of waste that is being processed, values for the main performance indicators used in the literature are presented for different feedstocks in Table 7.

3.4 Product Harvesting and Post-treatment

The BSF process yields two main products, namely mature BSF larvae, and the waste residue, whose properties, applications and post-treatment are described in the following sections and summarized in Table 8.

3.4.1 Product Yields

Product yields vary significantly depending on the waste type being processed. Overall, yield values reported in the literature for mature larvae and waste residue range respectively from 40 to 118 kg of larvae tonne of waste^{-1} and 210 to 810 kg of waste residue tonne of waste^{-1}, on a dry basis (Newton et al. 2005; Myers et al. 2008; Diener et al. 2011; Nguyen et al. 2013; Banks et al. 2014; Saragi and Bagastyo 2015; Rehman et al. 2017a). Yields of mature larvae and waste residue for different feedstocks can be deduced from, respectively, the bioconversion and the waste reduction rates presented in Table 7.

3.4.2 Harvesting Techniques

The technique used to separate the BSF from the waste residue depends on the stage at which it is being harvested, i.e. larval or prepupal stage. When harvesting is carried out at the prepupal stage, the most common method reported in the literature is self-harvesting, i.e. prepupae, naturally migrating from the waste to find a pupation site, are guided to a given location, typically via a ramp, to be harvested (Diener et al. 2011; Mutafela 2015; Popoff and Maquart 2016a). The advantage of self-harvesting is that it is a simple and non-labor-intensive method. On the other hand, to harvest the larvae before they turn into prepupae, a manual sieve or an automated shaking sieve are used (Popoff and Maquart 2016a; Cheng et al. 2017; Dortmans et al. 2017). Dortmans et al. (2017) recommended a sieve mesh size of 3 millimeters (mm) for manual sieving and 5 mm for automated sieving. Cheng et al. (2017) demonstrated that larvae could be harvested using a manual 2.36-mm sieve from the residue of food waste, whose initial moisture content was below 80% (wet basis).

On the other hand, if the initial moisture content of the waste is above 80% (wet basis), instead of obtaining a crumbly waste residue, the waste residue will be in the form of a slurry with unprocessed chunks (Cheng et al. 2017; Dortmans et al. 2017). In that case, Dortmans et al. (2017) suggested using non-shaking flat screens with a 5-mm mesh, through which both the liquid and larvae that want to avoid sunlight will flow and fall into a container placed below, while unprocessed chunks will remain on top of the screen. Larvae that have fallen through the mesh into the collection container can then be harvested from the liquid using a strainer spoon (Dortmans et al. 2017).

TABLE 7. BIOCONVERSION PERFORMANCE FOR DIFFERENT FEEDSTOCKS.

Feedstock	Waste reduction[a] (%)	Mean final larval weight[b] (mg)	Larval development time[c] (days)	Bioconversion rate[d] (%)	Food conversion ratio[e]	References
Pig manure	56 (DW)	113 (WW)	25-46	4 (DW)	10 (DW)	Newton et al. 2005; Nguyen et al. 2013; Banks et al. 2014
Dairy manure	33-58 (DW)	137-179 (WW)	26-30	2-4* (DW)	-	Myers et al. 2008
Chicken manure	50 (WW)	220 (WW)	-	4 (WW)	13 (WW)	Sheppard et al. 1994; Banks et al. 2014
Dairy manure and chicken manure	43-55 (DW)	60-100 (WW)	18-22	4-10 (DW)	6-10 (DW)	Rehman et al. 2017a
Human feces	25-55 (WW)	194-315 (WW)	-	2-22 (WW)	2-16 (WW)	Banks et al. 2014
MSW	66-79 (DW)	138-220 (WW)	-	12 (DW)	15 (DW)	Diener et al. 2011; Banks et al. 2014
Kitchen waste	-	173 (WW)	20-33	-	-	Nguyen et al. 2013
Restaurant waste	-	154 (WW)	19	-	-	Spranghers et al. 2017
Fruit and vegetables	43-64 (DW)	123 (WW)	22-40	-	-	Nguyen et al. 2013; Saragi and Bagastyo 2015
Vegetable waste	-	140 (WW)	16	-	-	Spranghers et al. 2017
Fish waste	19-54 (DW)	143 (WW)	20-36	-	-	Nguyen et al. 2013; Saragi and Bagastyo 2015
Overall range	**19-79**	**60-315**	**16-46**	**2-22**	**2-16**	

[a] Weight percentage of the initial waste added that is reduced over the feeding period.

[b] Mean weight of one larva at the end of the feeding period.

[c] Time required for the juvenile larvae added to the waste to reach the prepupal stage.

[d] Weight percentage of waste added that is converted into larval biomass. It indicates how many kilograms (kg) of mature larvae can be obtained from 100 kg of waste.

[e] Ratio of the weight of feed ingested and weight gained by the larvae over the feeding period. It measures the efficiency of the larvae to convert the feed ingested into body mass.

* Value obtained by using an equation : Dry feed intake (g) divided by Wet weight gain (g)

Note: DW: dry weight; WW: wet weight.

TABLE 8. BSF PRODUCTS' PROPERTIES AND APPLICATIONS.

	Mature BSF larvae	Waste residue
Yield	40-118 kg of larvae tonne of waste^{-1} (DW basis) Typically, 200 kg (WW) of larvae tonne of waste^{-1}	210-810 kg of waste residue tonne of waste^{-1} (DW)
Properties	High protein (40% DW) and lipid content (35% DW). Relatively rich in Ca, P and K. Main fatty acids: lauric acid, palmitic acid and oleic acid. Main essential amino acids: lysine, valine and leucine.	The waste residue contains nutrients, including increased concentrations of ammonium nitrogen. The residual C/N ratio depends on the initial C/N ratio of the input waste. pH between 7 and 8. Compost obtained is immature.
Safety	The levels of most chemical contaminants are lower than those recommended. The only chemical risk identified pertains to the bioaccumulation of cadmium in larvae. There is also a risk of presence of pathogens in larvae reared on animal or human waste despite the antibacterial properties of the larvae.	BSF waste treatment removes, in animal and human waste, bacteria from the Enterobacteriaceae family (*Salmonella* spp. and *E. coli*) under sufficient temperature (27-32 °C) and alkaline conditions but has no effect on the destruction of other pathogens such as *Enterococcus* spp., bacteriophage or *Ascaris suum* ova. BSF treatment also accelerates the degradation of different types of pharmaceuticals and pesticides in the waste.
Applications	The main application for BSF larvae is their use as feed ingredients for monogastric animals. The oil extracted from the larvae can also be used to produce biodiesel and the chitin contained in the exoskeleton of the larvae can be sold as a chelating agent.	Fertilizer
Post-treatment	Sanitization (e.g. boiling), drying, lipid extraction, etc.	Thermophilic composting or vermicomposting or anaerobic digestion
References	Hale 1973; Newton et al. 1977, 2005; Bondari and Sheppard 1981, 1987; Erickson et al. 2004; St-Hilaire et al. 2007a, 2007b; Diener 2010; Diener et al. 2011, 2015b; Li et al. 2011b; Sealey et al. 2011; Zheng et al. 2012a, 2012b; Caruso et al. 2013; Finke 2013; Lalander et al. 2013, 2016; Banks et al. 2014; Lock et al. 2014; Makkar et al. 2014; Charlton et al. 2015; Leong et al. 2015, 2016; Park et al. 2015; Tran et al. 2015; Cummins Jr. et al. 2017; Devic et al. 2017; Dortmans et al. 2017; Gao et al. 2017; Liu et al. 2017; Rehman et al. 2017a; Liland et al. 2017; Schiavone et al. 2017; Spranghers et al. 2017; Zurbrügg et al. 2018	Erickson et al. 2004; Newton et al. 2005; Liu et al. 2008; Choi et al. 2009; Diener et al. 2011; Green and Popa 2012; Lalander et al. 2013, 2015, 2016; Banks et al. 2014; Adeku 2015; Dortmans 2015; Saragi and Bagastyo 2015; Murray 2016; Dortmans et al. 2017; Lohri et al. 2017; Quilliam et al. 2017; Rehman et al. 2017a

Note: Ca = calcium; P = phosphorus; K = potassium.

3.4.3 Post-treatments

BSF Larvae

Further processing of the harvested larvae is usually required for sanitization, storage and transport purposes (Zurbrügg et al. 2018). Sanitization can be achieved by placing the larvae in boiling water for about two minutes, which kills off the bacteria on the larvae and allows them to empty their guts (Dortmans et al. 2017). Alternatively, Charlton et al. (2015) suggested washing the larvae with water and placing them in sawdust overnight to allow them to empty their guts. Then, depending on the market demand, the larvae can also be frozen or dried (Dortmans et al. 2017). Drying is particularly interesting as it is less energy-intensive and further sanitizes the product (Lalander et al. 2013). In addition, as the dry matter content of fresh prepupae is quite high (30 to 45%), dehydrating them could be easier and less costly compared to other fresh by-products (Newton et al. 2008; Makkar et al. 2014; Tran et al. 2015). Dortmans et al. (2017) recommended drying the larvae until their moisture content drops below 10% so they can be stored efficiently. The fat content should also be kept low for storage (Zurbrügg et al. 2018). Different drying methods are suggested in the literature. Charlton et al. (2015) suggested placing the larvae in a gas oven at 60 to 80 °C for two hours. Alternatively, solar drying is a low-cost and energy-saving solution particularly adapted to low-income and tropical countries. Caruso et al. (2013), who used bamboo baskets to sun dry BSF larvae in Indonesia, established that under a light intensity greater than 2,000 lux, a temperature of 38 °C and air humidity of about 50%, 17 hours of sunshine were required to dry 95% of the larvae. Caruso et al. (2013) also designed a hand-made oven consisting of a small electrical heater and a closed wooden structure to dry the BSF prepupae. Another refinement method consists of separating the larvae's lipids from the proteins in order to enhance feed formulation (Schiavone et al. 2017). Two main techniques are reported in the literature for oil extraction (or defatting), namely chemical extraction using petroleum ether as a solvent (Li et al. 2011a; Zheng et al. 2012a; Surendra et al. 2016), and mechanical extraction, which consists of, for example, cutting frozen larvae and pressing them (Schiavone et al. 2017; Zurbrügg et al. 2018). After the defatting process, the extracted oil can either be used as an animal feed ingredient or be converted into biodiesel (Li et al. 2011b; Zheng et al. 2012a, 2012b).

Waste Residue

The waste residue should preferably undergo a maturation phase before it can be used as a compost (Dortmans 2015; Lohri et al. 2017; Dortmans et al. 2017). This can be achieved through thermophilic aerobic composting, which enables reducing the residue volume as well as its phytotoxicity and pathogen content (Dortmans 2015). It has not been ascertained whether combining the BSF waste treatment process with composting could reduce composting time. Another option is to use the residue as a substrate for vermicomposting (Dortmans et al. 2017). Newton et al. (2005) ran primary tests whose results suggested that the residue from BSF processing of swine manure was a suitable substrate for vermicomposting. If the waste residue has a high moisture content and a suitable C/N ratio, typically 16 to 25, it can also be used for biogas production via anaerobic digestion (Dortmans et al. 2017; Lohri et al. 2017).

4. PRODUCTS: PROPERTIES AND APPLICATIONS

4.1 BSF Larvae

4.1.1 Properties of BSF Larvae

BSF larvae's chemical content varies depending on the type of waste used as a food source and the stage at which they are harvested (Spranghers et al. 2017; Liland et al. 2017; Liu et al. 2017). Figure 3 shows the average composition of a mature BSF larva, while Table 9 presents a more detailed analysis of the main nutritional attributes of mature BSF larvae, based on values reported by various studies.

FIGURE 3. AVERAGE COMPOSITION OF A MATURE BSF LARVA (% DM) (BASED ON DATA PROVIDED IN TABLE 9).

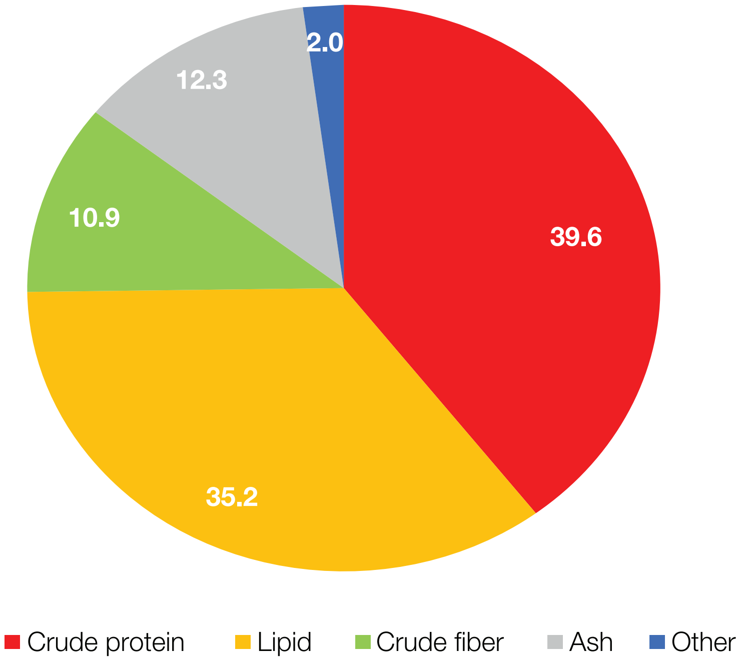

TABLE 9. GENERAL COMPOSITION OF MATURE BSF LARVAE.

Main components	Average value	Minimum value	Maximum value	Standard deviation	Number of studies reviewed
Crude protein (% DM)	39.6	35.0	43.6	2.7	8
Lipid (% DM)	35.2	13.9	49.0	9.5	7
Crude fiber (% DM)	10.9	7.0	24.4	6.7	3
Ash (% DM)	12.3	2.7	25.7	6.6	7
Dry matter of the fresh larva (% WW)	38.6	31.1	44.0	4.8	3
Chitin (% DM)	6.5	4.5	8.7	1.7	3
Gross energy (MJ kg^{-1} DM)	22.1	-	-	-	2

Sources: Based on data provided by Newton et al. 1977, 2008; Arango Gutiérrez et al. 2004; Barry 2004; St-Hilaire et al. 2007b; Diener et al. 2009b; Caruso et al. 2013; Makkar et al. 2014; Tran et al. 2015; Spranghers et al. 2017; Liland et al. 2017; Liu et al. 2017.

DM: Dry Matter; WW: Wet Weight

Regardless of the feedstock, BSF larvae are reported to exhibit high protein and fat contents (Banks 2014; Makkar et al. 2014; Tran et al. 2015; Liu et al. 2017). As shown in Table 9, they consist of about 35 to 44% DM: Dry Matter of crude protein. The lipid content varies significantly, from 14 to 49% DM (see Table 9), depending on the waste fed to the larvae and its lipid profile (Makkar et al. 2014; Tran et al. 2015; Liland et al. 2017). Lipid content values reported in the literature for various feedstocks are presented in Table 10.

The ash content is relatively high (12% DM on average), though highly variable (3 to 26% DM), as shown in Table 9 (Newton et al. 2005; St-Hilaire et al. 2007b; Caruso et al. 2013; Makkar et al. 2014; Spranghers et al. 2017). The fatty acid profile of BSF larvae depends on the feedstock's fatty acid profile (Tran et al. 2015; Liland et al. 2017). Some general trends have been highlighted in the literature. Leong et al. (2015) and Spranghers et al. (2017) reported that the fatty acid profile of BSF larvae is mostly composed of saturated fatty acids, which represent around 65 to 90% in weight (DM basis) of the total lipid in BSF larvae, depending on the feedstock. In addition, the most abundant fatty acids in the BSF lipid profile are reported to be lauric acid (C12:0), palmitic acid (C16:0) and oleic acid (C18:1n9c) (St-Hilaire et al. 2007a; Caruso et al. 2013; Finke 2013; Leong et al. 2015, 2016; Spranghers et al. 2017). Table 11 shows, for different feedstocks, the proportions reported in the literature for these three fatty acids.

TABLE 10. LIPID CONTENT OF BSF LARVAE OBTAINED FROM DIFFERENT FEEDSTOCKS.

Waste type	Lipid content (% DM)	References
Poultry manure	14-35	Bondari and Sheppard 1981; Sheppard et al. 1994; Arango Gutiérrez et al. 2004
Pig manure	28-36	Newton et al. 2005
Cattle manure	35	Newton et al. 1977
Fruit waste	42-44	Leong et al. 2015; Mutafela 2015
Vegetable waste	37	Spranghers et al. 2017
Restaurant waste	39	Spranghers et al. 2017
Oil-rich food waste	42-49	Barry 2004
Sewage sludge	30	Leong et al. 2015
Palm kernel meal	33-43	Caruso et al. 2013
Palm decanter cake	37	Leong et al. 2015

TABLE 11. PROPORTIONS OF SELECTED FATTY ACIDS IN BSF LARVAE FOR DIFFERENT FEEDSTOCKS.

Feedstock	Lauric acid (C12:0)*	Palmitic acid (C16:0)*	Oleic acid (C18:1n9c)*	References
Cow manure	21-36	16	24-32	St-Hilaire et al. 2007a; Li et al. 2011a, 2011b
50% fish offal and 50% cow manure	43	11	12	St-Hilaire et al. 2007a
Fruit waste	76	-	-	Leong et al. 2015, 2016
Vegetable waste	61	9	6	Spranghers et al. 2017
Restaurant waste	58	10	8	Spranghers et al. 2017
Palm decanter	48	25	16	Leong et al. 2016

* Values are presented as weight percentage of the total lipid, on a DM basis.

Regarding mineral composition, BSF larvae are relatively rich in calcium (9 to 86 g kg^{-1} DM), phosphorus (4 to 5 g kg^{-1} DM) and potassium (5 to 6 g kg^{-1} DM) (Newton et al. 1977; Finke 2013; Makkar et al. 2014; Spranghers et al. 2017). As for the essential amino acid profile, BSF larvae are particularly rich in lysine, valine and leucine (Finke 2013; Makkar et al. 2014; Tran et al. 2015; Spranghers et al. 2017; Liland et al. 2017).

Several authors have investigated how to enhance BSF larvae nutritional content through their diet. In this regard, St-Hilaire et al. (2007a) reported that combining dairy manure with fish offal in BSF larvae's diet yields larvae richer in omega 3 fatty acid, compared to larvae fed on only dairy manure. Liland et al. (2017) also established that including seaweed in larvae's diet enriches the biomass in valuable nutrients, such as EPA (omega 3 fatty acid), iodine and vitamin E. In addition, Mohd-Noor et al. (2017) observed that fermenting the waste from coconut milk extraction for four weeks improved the protein and fat contents of BSF larvae.

4.1.2 Use of BSF Larvae as Animal Feed

The high protein and fat content of BSF larvae suggests their potential use as animal feed, making them an interesting alternative to unsustainable and increasingly expensive soybean meal and fishmeal, conventionally used as feed in animal production (Diener 2010; Spranghers et al. 2017; Surendra et al. 2016). Various studies have shown promising results as regards animal feeding with BSF prepupae. Substituting partly or completely conventional feed with BSF larvae yielded satisfactory results in terms of growth and quality for various monogastric animal species, including fish, such as channel catfish (*Ictalurus punctatus*) (Bondari and Sheppard 1981, 1987; Newton et al. 2005), blue tilapia (*Oreochromis aureus*) (Bondari and Sheppard 1981, 1987), Nile tilapia (*Oreochromis niloticus*) (Devic et al. 2017), rainbow trout (*Oncorhynchus mykiss*) (Sealey et al. 2011; St Hilaire et al. 2007b), Atlantic salmon (*Salmo salar*) (Lock et al. 2014), and crustaceans, such as Pacific white shrimp (*Litopenaeus vannamei)* (Cummins Jr et al. 2017), as well as livestock, such as pigs (Newton et al. 1977) and chickens (Hale 1973).

However, Makkar et al. (2014) recommended conducting additional feeding experiments as some studies have reported reduced growth performance and because the results depend on the type of feedstock used to feed the larvae (Spranghers et al. 2017). The literature also highlights the need to improve the larvae-based feed formulation, especially the protein, fat and fiber ratio (Diener 2010; Newton et al. 2008). In this regard, several authors suggested that separating the protein from the fat and the chitin would allow the formulation of a more balanced diet and enhance the digestibility and feeding value of the larvae, i.e. defatted larvae exhibit a higher protein content of about 60% compared to whole larvae (Diener 2010; Newton et al. 2005, 2008; Dortmans et al. 2017; Schiavone et al. 2017).

Another issue concerns the optimum stage at which the larvae should be harvested to be refined as animal feed. Some authors suggested that harvesting larvae before they reach the prepupal stage may yield a higher value feed product (Popoff and Maquart 2016a; Dortmans et al. 2017). Liu et al. (2017), who analyzed the evolution of the nutritional content of the BSF throughout its lifecycle, observed that crude protein and fat contents reach the highest levels at the early prepupal stage. However, nutritional value trades off with digestibility. Prepupae have indeed a higher chitin content than larvae, which makes them less digestible for chickens and fish (Caruso et al. 2013; Dortmans et al. 2017). Therefore, some authors, who conducted feeding trials, reported having used mature larvae that had not reached the prepupal stage (Bondari and Sheppard 1987; Devic et al. 2017), while others used prepupae (Newton et al. 2005; St-Hilaire et al. 2007b).

Charlton et al. (2015), investigating the chemical safety of using BSF larvae as a source of protein for animal feed, measured the level of a wide range of chemical contaminants (1,140 compounds analyzed), including veterinary medicines, pesticides, heavy metals, dioxins, polychlorinated biphenyls, polyaromatic hydrocarbons and mycotoxins, in BSF larvae reared on agroindustrial waste. They reported that all the concentrations recorded were lower than the maximum levels recommended by organizations including the European Commission, the World Health Organization and the Codex Alimentarius (See Table 12). However, they warned against the potential risk of bioaccumulation of metals, especially cadmium in the larvae. Studies have shown that heavy metals may accumulate in larvae, though with different accumulation patterns depending on the metal. When feeding BSF larvae with contaminated substrates, concentrations of heavy metals recorded in the larvae and prepupae's body, compared to those in the initial feedstock, are higher for cadmium, the same for zinc, lower for chromium and zero for lead (Diener et al. 2015b; Gao et al. 2017). Therefore, Lohri et al. (2017) recommended not using waste contaminated by heavy metals as feedstock in BSF waste treatment. Concerning pharmaceuticals and pesticides, findings by Charlton et al. (2015) are supported by a study by Lalander et al. (2016), who observed no bioaccumulation in BSF larvae fed with waste containing different pharmaceuticals and pesticides.

TABLE 12. RECOMMENDED STANDARDS FOR SELECTED CHEMICAL CONTAMINANTS.

Chemical contaminants	Maximum level	References
Heavy metals[a]		
Arsenic	2 mg kg^{-1} (or ppm)	EC Directive 2002/32/EC
Cadmium	2 mg kg^{-1} (ppm)	
Fluorine	500 mg kg^{-1} (ppm)	
Lead	10 mg kg^{-1} (ppm)	
Mercury	0.1 mg kg^{-1} (ppm)	
Dioxins, polychlorinated biphenyls (PCB) and polyaromatic hydrocarbons (PAH)		
PCB ICES-6[b]	10 µg kg^{-1}	EC Directive 2002/32/EC amendment 277/2012/EC
WHO-TEF[c]	0.75 ng kg^{-1}	EC Directive 2002/32/EC
PAH4	1-35 µg kg^{-1}	EC regulation 1881/2006 amendment 835/2011

[a] For a moisture content of 12%.

[b] ICES-6 is a set of 6 PCBs, namely PCB28, PCB52, PCB101, PCB138, PCB153 and PCB180.

[c] World Health Organization toxic equivalency factor (TEF).

As for microbiological risks, Zheng et al. (2013b), who surveyed bacterial diversity throughout the BSF lifecycle using pyrosequencing, observed the presence of bacteria from six different phyla, Bacteroidetes and Proteobacteria being the most represented as they accounted for two-thirds of the bacteria identified. Among the bacteria present throughout the whole BSF lifecycle, they identified Enterobacterials and Xanthomonadales as potential pathogens. In addition, BSF larvae can be contaminated by some pathogens contained in the waste processed. In particular, both Erickson et al. (2004) and Lalander et al. (2013) found *Salmonella* spp. in larvae following exposure to contaminated animal and human feces, respectively. Lalander et al. (2013) also reported the presence of *Ascaris suum* ova inside the larvae and prepupae. However, they observed that the concentration of these organisms was lower in the gut of the prepupae than in the gut of the larvae, suggesting that the prepupae empty their gut before migrating to their pupation site. Therefore, using prepupae rather than larvae as animal feed may be safer. Regarding plant pathogens, Park et al. (2015), by analyzing the antibacterial properties of larval extract from BSF, established that larval extract also plays a key role in the defence against plant pathogens. However, Charlton et al. (2015), who did not analyze microbiological risks associated with using BSF larvae as animal feed, pointed out that such risks can be significantly minimized via appropriate postprocessing techniques (see Section 3.4.3).

4.1.3 Production of Biodiesel

The production of biodiesel from BSF larvae's oil is also being explored. Several studies have shown, based on the fatty acids profile, that lipids of BSF larvae fed on various feedstocks, such as food waste (Surendra et al. 2016; Zheng et al. 2012a, 2012b), fruit waste (Leong et al. 2016), sewage sludge (Leong et al. 2016), cattle, chicken and pig manure (Li et al. 2011b), palm decanter cake from an oil palm mill (Leong et al. 2016) and rice straw (Zheng et al. 2012a), could be suitable for biodiesel production. Table 13 presents the biodiesel yields obtained for the different feedstocks.

TABLE 13. BIODIESEL YIELDS OBTAINED FOR DIFFERENT FEEDSTOCKS (1,000 BSF LARVAE PER KG WASTE).

Feedstock	Biodiesel (mg per larvae)	References
Cattle manure	35.6	Li et al. 2011b
Pig manure	57.8	Li et al. 2011b
Chicken manure	91.4	Li et al. 2011b
Restaurant waste	23.6	Zheng et al. 2012b
Mixture of rice straw (30%) and restaurant waste (70%)	21.9	Zheng et al. 2012a

Newton et al. (2005) suggested that the production of biodiesel from the oil of BSF larvae fed on swine manure would yield as much energy as anaerobic digestion of that same manure. Moreover, the fuel properties of the biodiesel produced from the lipids of BSF larvae fed on animal manure are comparable to those of other biodiesels, such as rapeseed oil-based biodiesel (Li et al. 2011b). In addition, according to Zheng et al. (2012a, 2012b), the biodiesels produced from BSF larvae fed on rice straw and restaurant waste meet most criteria of the European standard EN 14214. The fuel properties of BSF larvae's fat-based biodiesel are compared to those of rapeseed-oil-based biodiesel and the EN 14214 standard in Table 14.

TABLE 14. FUEL PROPERTIES OF THE BIODIESEL PRODUCED FROM BSF LARVAE'S LIPIDS.

Fuel properties	EN 14214 standard	BSF larvae's fat-based biodiesel*	Rapeseed oil-based biodiesel	References
Density (kg m^{-3})	860-900	860-895	880-911	Li et al. 2011b; Zheng et al. 2012a, 2012b
Viscosity at 40 °C (mm^2 s^{-1})	3.5-5.0	4.9-6.0	4.4-5.8	
Ester content (%)	> 96.5	96.5-97.2	-	
Flash point (°C)	> 120	123-128	-	
Cetane number	> 51	53-58	45	

* Range of values for BSF larvae fed on animal manure, restaurant waste and rice straw.

4.1.4 Production of Chitin

Besides the high protein and lipid content of BSF larvae, which can be taken advantage of for animal feeding and biodiesel production, another valuable product could be extracted from BSF larvae, namely chitin, which is a main component of the larvae's cuticle, or exoskeleton. From a commercial point of view, chitin is an interesting compound because it exhibits a high nitrogen content (6.9%) compared to synthetic cellulose (Diener 2010; Caruso et al. 2013). It can be used as a chelating agent in medicines, cosmetics, biotechnologies, phytosanitary and industrial products (Kumar 2000; Caruso et al. 2013; Younes and Rinaudo 2015). Extracting chitin from BSF larvae and selling it on specific markets could increase the economic value derived from the larvae. However, the economic feasibility of extracting chitin from BSF larvae has not yet been investigated (Diener 2010). As the literature does not discuss the yield that could be expected for chitin production from BSF larvae, it is hard to assess whether BSF larvae constitute a relevant source of chitin, compared to crab and shrimp shells, which are so far the main commercial sources of chitin (Younes and Rinaudo 2015).

4.2 Waste Residue

4.2.1 Properties

Compared to larvae, few studies have analyzed the properties of the waste residue. Lalander et al. (2015) reported that processing a mixture of pig manure, dog food and human feces by the BSF increased the concentration of total phosphorus per gram of total solids in the waste residue by 45% and that of total ammonium nitrogen (NH_4^+-N) by almost 160%, suggesting its potential use in agriculture as a soil amendment. The potential of BSF larvae to convert organic nitrogen into ammonium nitrogen was also observed by Green and Popa (2012), who established that BSF feeding on vegetal and food waste significantly enhance nitrogen mineralization. They observed that the concentration of ammonium in the leachate increased by five to six times. The C/N ratio of the waste residue depends on the initial C/N ratio of the feedstock. Values reported by the literature for the C/N ratio of the final waste residue range from 10 to 43 (Lalander et al. 2015; Saragi and Bagastyo 2015; Rehman et al. 2017a), which corresponds to the same range reported for the C/N ratio of the feedstock.

The pH of the waste residue typically ranges from 7 to 8 (Choi et al. 2009; Dortmans 2015; Lalander et al. 2015; Rehman et al. 2017a), which is within the optimal range for plant growth according to Rehman et al. (2017a). The moisture content of the waste residue depends on the initial moisture content of the waste. For food waste, Cheng et al. (2017) observed that when the initial moisture content was 70% and 75%, the moisture content of the waste residue at the end of the feeding period had decreased to about 50%. On the other hand, when the initial moisture content was 80%, it did not decrease and remained above 80% throughout the BSF waste treatment process.

4.2.2 Use as Fertilizer

Few studies have investigated the efficiency of BSF waste residue, raw or postprocessed, as a fertilizer for different crops. Choi et al. (2009) reported promising results pertaining to the use of the waste residue (no information regarding the post-treatment), yielded by the bioconversion of food waste by the BSF, as a substitute for conventional fertilizer. They observed no significant difference between the chemical composition of the BSF waste residue and a commercial fertilizer (name not specified). In addition, they reported that the growth rate and chemical composition of Chinese cabbages grown on BSF residue were similar to those of cabbages grown on commercial fertilizer. Similarly, agronomic trials conducted in Ghana showed that applying BSF biofertilizer (i.e. BSF waste residue composted for one to three weeks) at 10 tonnes ha^{-1} together with inorganic fertilizer could increase crop yield by up to 55% compared to applying inorganic fertilizer alone for various local short-cycle cash crops, especially shallots (onion) and maize. In addition, applying BSF biofertilizer alone yielded better results compared to the application of poultry manure combined with inorganic fertilizer (Adeku 2015; Murray 2016; Quilliam et al. 2017). On the other hand, Newton et al. (2005) reported poor performance related to the growth of basil (*Ocimum basilcum*) and sudan grass (*Sorghan sudanense*) grown on swine manure processed by BSF larvae (no post-treatment) mixed with either clay or sand. This could be attributed to the immaturity of the waste residue obtained from the BSF process, as reported by Dortmans et al. (2017) and Lohri et al. (2017), which results in oxygen depletion in the soil following its application and inhibits plant growth (Brinton and Evans 2001). Therefore, the residue should preferably undergo a maturation phase (Dortmans 2015; Lohri et al. 2017; Dortmans et al. 2017).

4.2.3 Safety

To investigate safety aspects regarding the use of waste residue from BSF waste treatment as a crop fertilizer and assess the risk of cross-contamination of crops, several studies have analyzed the efficiency of BSF waste treatment to reduce pathogens and toxic substances, such as pesticides, or pharmaceuticals, contained in the initial waste. Concerning pathogens, studies have focused on excreta from animals and humans as they can host food-borne pathogens, such as *Salmonella* spp. and *E. coli*, which can be transferred to their feces. The literature suggests that BSF waste treatment removes bacteria successfully from the Enterobacteriaceae family, as accelerated reduction of *Salmonella* spp. and/or *E. coli* was observed in human feces, chicken manure and dairy manure (Erickson et al. 2004; Liu et al. 2008; Lalander et al. 2013, 2015). In chicken manure, most of pathogen inactivation by the BSF occurs within one to three days (Erickson et al. 2004), while eight days are required to reduce *Salmonella* spp. in human feces (Lalander et al. 2013). Erickson et al. (2004) suggested that BSF larvae are able to inactivate some pathogens thanks to antimicrobial activities in their alimentary tracts.

However, the ability of the BSF to reduce *E. coli* depends on the temperature (Erickson et al. 2004; Liu et al. 2008). Erickson et al. (2004) observed greater pathogen reduction by the BSF in chicken manure at 27°C and 32°C than at 23°C, while Liu et al. (2008), comparing pathogen reduction by the BSF in dairy manure at 23, 27, 31 and 35°C, reported the greatest reduction at 27°C. The antimicrobial activity of BSF larvae also seems to be affected by the pH and to be efficient only under alkaline conditions since Erickson et al. (2004) observed pathogen reduction in alkaline chicken manure but not in acidic hog manure. BSF larvae may also be able to reduce plant pathogens in the waste processed, because the larval extract from BSF was found to have significant antibacterial activity against plant pathogens (Park et al. 2015).

On the other hand, BSF waste treatment was reported to have no effect on the destruction of other pathogens, such as *Enterococcus* spp., bacteriophage or *Ascaris suum* ova (helminth eggs) (Lalander et al. 2013; Lohri et al. 2017). Finally, BSF waste treatment may stem the spread of pharmaceuticals and pesticides contained in waste into the environment as Lalander et al. (2016) reported that BSF waste treatment was able to accelerate the degradation of different types of pharmaceuticals and pesticides, such as carbamazepine, roxithromycin, trimethoprim, azoxystrobin and propiconazole in the waste.

5.ECONOMIC, ENVIRONMENTAL, LEGAL AND SOCIAL DIMENSIONS OF THE BSF TECHNOLOGY

5.1 Economic Impact

Globally, there are privately own and managed businesses operating in the field of waste treatment for larvae and residue production. However, to maintain their competitive advantage, these companies prefer not to disclose their operational processes and profits generated (Zurbrügg et al. 2018). It is therefore not surprising to note that only few studies address the economic dimension of the BSF technology, and most research focuses on the biological aspect of the process. Moreover, the studies that do analyze the economic viability of the BSF technology rely often on extrapolations from experimental or pilot systems to commercial facilities or are based on case studies with numerous simplifying assumptions (Cicková et al. 2015). Table 15 summarizes the economic data pertaining to the BSF technology provided in the literature.

5.1.1 Economic Benefits

Most economic benefits associated with the BSF technology lie in the fact that this treatment method valorizes low-value organic waste into high-value protein at relatively low cost (Spranghers et al. 2017; Diener et al. 2009b). The main economic benefits suggested in the literature are the revenues from the sales of the larvae and potentially the waste residue, as well as cost savings on management of the organic waste, due to mass and pollutant potential reduction (Barry 2004; Amatya 2008; Alvarez 2012). Therefore, to evaluate the economic benefits of a BSF treatment facility for manure, Amatya (2008) used two indicators, i.e. the manure bulk reduction rate and the economic value of the larvae. Amatya (2008) also suggested to economically assess the cost savings related to the reduction of the pollution potential of waste, associated with the BSF process, to improve the economic evaluation, which was done by Newton et al. (2005). The reported economic benefits and costs are summarized in Table 15.

TABLE 15. ECONOMIC BENEFITS AND COSTS ASSOCIATED WITH A BSF FACILITY.

	Parameter	Value	Comments	References
Economic Benefits	Selling price for the larvae (animal feed) (USD tonne of larvae meal^{-1})	Range: 200-2,000; Average: 965 Typically 390, in indonesia	Studies conducted in the USA, Costa Rica and Tanzania. The value depends on the market targeted (e.g. aquaculture or poultry feed) and the grade of the product (degree of refining)	Tomberlin and Sheppard 2001; Newton et al. 2005; Diener et al. 2009a; OVRSol 2010; Agrawal et al. 2011; Zurbrügg et al. 2018
	Value of dry larvae (animal feed) (USD tonne of waste treated^{-1})	Sweden: 126 (feces) – 137 (food waste) Sub-Saharan Africa: 22-32 (fecal sludge)		Diener et al. 2014; Lalander et al. 2017
	Annual revenue from the sales of larvae as animal feed ingredients (USD year^{-1} tonne daily input^{-1})	Range: 6,500 (19 kg of larvae tonne of waste^{-1} day^{-1}, DW)[a] – 20,000 (50 kg of larvae tonne of waste^{-1} day^{-1}, DW)[b]; average: 13,250	Besides the selling price, this value depends on the performance of the BSF facility, i.e. the daily weight of larvae produced per tonne of waste treated (indicated in brackets)	[a] Popoff and Maquart 2016b [b] Diener et al. 2009a
	Annual revenue from the sales of the waste residue as a soil amendment (USD year^{-1} tonne daily input^{-1})	6,300 (yield: 230 kg of compost tonne of waste^{-1} day^{-1})	The ability of the waste residue to contribute to the revenue of a BSF waste treatment facility is questioned by some authors, while other authors point out the difficulty to estimate a price for this product as there is no established market for vermicompost	Popoff and Maquart 2016b
	Value of the waste residue as a soil amendment USD tonne of waste treated^{-1})	Sweden: 29 (feces) – 33 (food waste) Sub-saharan africa: 7-16 (fecal sludge)		Diener et al. 2014; Lalander et al. 2017
	Cost savings on organic waste disposal	75% for swine manure, 85% for cow manure, 20% for food waste	All these studies were conducted in North America	Barry 2004; Newton et al. 2005; Amatya 2008
Costs	Space requirement (m^2 tonne daily input^{-1})	140-640 for medium-scale facilities and 40-50 for large-scale facilities	Medium-scale capacity: 100 kg to 10 tonnes of waste day^{-1} Large-scale capacity: > 100 tonnes of waste day^{-1}	Diener et al. 2009a; and data provided in the case studies
	Infrastructure costs (USD tonne daily input^{-1})	13,000-18,000 for medium-scale facilities and 32,000-75,000 for large-scale facilities	-	Diener et al. 2009a; and data provided in the case studies
	Infrastructure costs (USD m^{-2})	30-35 for medium-scale facilities and 900-1,400 for large-scale facilities	-	Diener et al. 2009a; and data provided in the case studies
	Total investment costs (USD tonne daily input^{-1})	23,000-28,000	Data available only for developing countries	Diener et al. 2009a; Popoff and Maquart 2016b
	Labor requirement (number of operators tonne daily input^{-1})	1-3 for medium-scale facilities and 0.3-0.4 for large-scale facilities	-	Diener et al. 2009a; and data provided in the case studies
	Labor cost (USD tonne daily input^{-1})	1,900 (160)-7,700 (390)	The numbers in brackets are the average wages for developing countries on which the calculation of the labor cost is based on (in USD month^{-1})	Diener et al. 2009a; Popoff and Maquart 2016b
	Labor cost (USD kg of larvae^{-1})	0.11-0.14 (WW) 0.43-0.85 (DW)	Data available only for developing countries	Diener et al. 2009a; Caruso et al. 2013; Popoff and Maquart 2016b
	Water and energy costs (USD m^{-2} year^{-1})	0.45-4.6 In tropical countries; 33 in Northern countries	-	Diener et al. 2009a; Alvarez 2012; Popoff and Maquart 2016b

(Continued)

TABLE 15. ECONOMIC BENEFITS AND COSTS ASSOCIATED WITH A BSF FACILITY. (CONTINUED)

Parameter	Value	Comments	References
Total running costs (USD year^{-1} tonne daily input^{-1})	~ 12,000 – 18,000	Data available only for developing countries. Running costs are reported to be two to four times lower than investment costs	Diener et al. 2009a; Popoff and Maquart 2016b; Zurbrügg et al. 2018
Overall performance (yearly profit)	Food waste: USD 90 tonne^{-1} year^{-1} in Canada; BSF manure management system: USD 100-280 cow^{-1} year^{-1}, USD 25,000 poultry house^{-1} year^{-1} in the USA; fecal sludge: USD 116,000 year^{-1} for processing the waste from 3 latrines day^{-1} in Tanzania		Newton et al. 2005; Amatya 2008; Agrawal et al. 2011; Alvarez 2012

Market Opportunities and Economic Value of Larvae

As market prices for fishmeal and soybean meal are rising due to increasing demand, and feed accounts for 60 to 70% of the total animal production costs, the industry is actively investigating alternative protein sources to supplement or even substitute for these conventional feed sources. As a result, insects have become an attractive feed solution, including BSF, which constitutes one of the most promising insect species for industrial feed production (van Huis et al. 2013; van Huis 2013; Spranghers et al. 2017). Therefore, a significant increase in conventional animal feed market prices may ensure the economic viability of producing BSF larvae for animal feed (Makkar et al. 2014; Lalander et al. 2015). Moreover, using BSF larvae as animal feed opens great market opportunities, as the International Feed Industry Federation (2017) estimated the annual world feed production at 1 billion tonnes, worth USD 400 billion.

Regarding the market price for larvae, a wide range of values is suggested in the literature. As there is no established market for larvae meal, Amatya (2008) suggested considering the market price for its substitutes, such as fishmeal or soybean meal. Indeed, van Huis et al. (2013) argued that insect-based feed, such as BSF larvae products, could have a similar market to soybean meal and fishmeal, which currently dominate the market of feed products for aquaculture and livestock. Specifically, it was assessed as part of the European Union (EU)-funded project PROteINSECT which investigated the use of insects as a novel protein source for animals, that the value of dipteran insect meal is at least twice that of soybean meal but lower than that of fishmeal (FERA 2016). According to Caruso et al. (2013), the sale price for BSF products depends on the market segment targeted. For example, prices are higher on the pet food market but it is smaller than that of aquaculture or livestock production.

Despite the absence of an established market, some authors tried to quantify the economic value of larvae. For instance, Tomberlin and Sheppard (2001) estimated this value at USD 200 tonne of larvae^{-1} (not specified whether fresh or processed larvae) and Newton et al. (2005), based on the value of menhaden fishmeal, at USD 355 tonne of larvae meal^{-1}. Some authors, on the other hand, suggested higher prices. For instance, Diener et al. (2009a), based on the 2009 market value of fishmeal, suggested a selling price on the aquaculture feed market of USD 1,000 tonne of dry larvae^{-1} (In 2017, this price was around USD 1,100 tonne^{-1}, see www.indexmundi.com.) In addition, Agrawal et al. (2011), studying the poultry feed market in Dar es Salaam (Tanzania), proposed two different selling prices, depending on whether the larvae were defatted, i.e. USD 700 for 1 tonne of low grade BSF larvae meal (protein content of about 40%) and USD 1,000 for 1 tonne of high grade BSF larvae meal (protein content of about 60%). In Indonesia, Zurbrügg et al. (2018) reported a potential sales value of about USD 390 tonne of dry larvae^{-1}. Finally, OVRSol (2010), a BSF company founded by Dr. Craig Sheppard and Dr. Larry Newton, two leading experts on organic waste bioconversion by the BSF, reported that this value could be as high as USD 1,500 to 2,000 tonne of insect biomass^{-1} (not specified whether DW or WW), depending on the application. In addition, they pointed out that this value could be even higher if the different components (protein, fat and chitin) were separated (OVRSol 2010).

Regarding the value of the chitin that could be extracted from BSF larvae, Caruso et al. (2013) reported that its price could vary significantly, from about USD 5,000 to 100,000 tonne^{-1}, depending on its purity and application. In addition, some authors assessed the market value of dry BSF larvae produced from one unit of waste treated (treatment costs not included). In the Swedish context, Lalander et al. (2017) estimated that the sales of dry BSF larvae would yield USD 137 tonne of food waste treated^{-1} and USD 126 tonne of feces treated^{-1}, while Diener et al. (2014), by studying the market demand for fecal sludge-derived products in three Sub-Saharan African cities (Dakar, Accra and Kampala) assessed the market value of dry BSF larvae at USD 22 to 32 tonne of fecal sludge^{-1}. A summary of these values can be found in Table 15, as well as an estimation of the annual revenue that could be yielded from the sale of the larvae as animal feed.

Market Opportunities and Economic Value of the Waste Residue

Among the few studies that quantified the economic benefits related to a BSF facility, almost none considered the revenue derived from the sales of the waste residue as a fertilizer. In view of the negative results regarding the efficiency of the BSF waste residue to promote plant growth, reported by Newton et al. (2005), Diener (2010) even questioned the ability of the waste residue from the BSF process to contribute to the revenue of a BSF waste treatment facility.

According to Salomone et al. (2017), the economic value of the waste residue is 100 to 200 times lower than that of larvae, making its contribution negligible. However, more recent agronomy trials, conducted to test the efficiency of BSF biofertilizer, yielded promising results (Choi et al. 2009; Adeku 2015; NZWC 2015; Enterra 2017c), suggesting that the waste residue from the BSF process could after all constitute an interesting source of additional income for BSF facilities (Caruso et al. 2013). In this regard, Enterra Feed, a Canadian venture operating a large-scale BSF facility near Vancouver, estimated that, in terms of tonnage, its 2015 sales of biofertilizer were similar to those of larvae-based feed ingredients (Enterra 2015). However, the total economic value derived from this product is hard to assess as existing industrial BSF facilities do not share the price of their products publicly.

In addition, Caruso et al. (2013) pointed out that the price of biofertilizer depends on various parameters, including its quality, origin, availability and the local market demand. Zering (2013), analyzing the costs and profits associated with a BSF manure management system in North Carolina, USA, suggested that the value of BSF waste residue could be similar to that of vermicompost, which is also difficult to assess as there is no well-established market for this product in the case of North Carolina. Popoff and Maquart (2016b) calculated that a BSF waste treatment plant producing about 230 kg of compost tonne of waste^{-1} day^{-1} could earn annual revenue of USD 6,300 per tonne of daily input from the sale of this compost. However, no information is available regarding how the price for the compost was established. In addition, Popoff and Maquart (2016b) considered that the annual revenue of the BSF plant was almost evenly distributed between the sales of the larvae and those of the compost.

Regarding the value of the waste residue per unit of waste treated, Lalander et al. (2017) estimated that in Sweden it is USD 33 per tonne of food waste treated and USD 29 per tonne of feces treated. On the other hand, Diener et al. (2014) assessed the value of the waste residue in Sub-Saharan cities at USD 7 to 16 per tonne of fecal sludge treated. Data pertaining to waste residue in this context are summarized in Table 15.

5.1.2 Costs Associated with the Process

For a BSF-based waste processing plant, costs can be classified as fixed or variable based on how they respond to a variation in the business activity. Fixed Costs, which include capital costs (i.e. construction, land acquisition, and capital) remain unchanged, regardless of the production level, but only as long as the production does not require additional machinery. Fixed costs could also include periodic costs like depreciation, rent and insurance. All other costs such as supplies, labour and utility charges which change proportionally with the activity level are categorized as variable costs (Zurbrügg et al. 2018).

Data on the costs associated with constructing and operating a commercial BSF waste treatment plant are scarce. However, a few studies have analyzed the costs related to BSF technology based on experimental- or pilot-scale BSF waste treatment units. These studies discussed both fixed costs (construction and equipment costs), and variable costs (labor, operation and maintenance of the facility, etc.) associated with a BSF waste treatment facility (Amatya 2008; Diener et al. 2009a; Caruso et al. 2013; Popoff and Maquart 2016b; Zurbrügg et al. 2018). Data provided in the literature on costs associated with BSF waste treatment are summarized in Table 15.

Investment Costs

According to Diener (2010) and Bucher and Peterhans (2016), BSF technology does not require high investment costs compared to other organic waste valorization methods, which makes it particularly suited to low- and middle-income settings, characterized by limited financial resources (Ponce Jara 2015). Table 16 presents the infrastructure costs for a few existing facilities with different capacities and a fictitious treatment plant in Costa Rica whose associated costs were estimated by Diener et al. (2009a) based on an extrapolation from laboratory experiments. Additionally, relevant ratios have been calculated to identify general trends regarding waste treatment capacity, space requirement and infrastructure costs.

As shown in Table 16, large-scale BSF facilities (daily capacity of at least 100 tonnes of waste) require only 40 to 50 m^2 to treat 1 tonne of waste, while smaller facilities need several hundreds of square meters to process the same amount of organic waste. On the other hand, in medium-scale facilities (daily capacity of hundreds of kilograms to a dozen tonnes of waste) infrastructure costs, compared to the capacity or the area, are much lower than in large-scale facilities. This is because larger facilities are largely automated and are thus more efficient in terms of quantity of waste treated per unit of area but on the other hand require larger investments to treat 1 tonne of waste or build 1 square meter.

Regarding the repartition of the infrastructure costs between the different units of a BSF facility, it seems that the breeding unit is the costliest to build. Barry (2004) listed the costs of the equipment and materials used to build a bench-scale on-site BSF facility for the valorization of food waste produced on the campus of North Texas University. Those costs amounted to approximately USD 5,600, 90% of which accounted for the breeding unit, especially the greenhouse. Similarly, Caruso et al. (2013) also calculated that, for a pilot BSF installation in Indonesia, about 75% of the building costs was allocated to the construction of the breeding unit. Total investment costs (infrastructure costs, equipment costs, land buying, etc.) available in the literature are presented in Table 15 according to the daily waste treatment capacity.

Labor Costs

Table 17 presents the number of operators or employees needed to run a BSF facility depending on the waste treatment capacity, and corresponding labor costs when available.

TABLE 16. COMPARISON OF INFRASTRUCTURE COSTS, SPACE REQUIREMENT AND CAPACITY OF SEVERAL BSF WASTE TREATMENT PLANTS.

Facility[a]	Location	Capacity (tonne of waste day^{-1})	Area (m^2)	Infrastructure costs (USD)	Ratio area/capacity (m^2 tonne daily input^{-1})	Ratio infrastructure cost/capacity (USD tonne daily input^{-1})	Ratio infrastructure cost/area (USD m^{-2})
Ento-Prise (Case study 3)	Ghana	0.33	212	6,090	~640	~18,000	~30
FORWARD (Case study 1)	Indonesia	3	424	- [b]	~140	-[b]	-
Fictitious plant[c]	Costa Rica	3	1,100	40,000	~370	~13,000	~35
Enterra Feed (Case study 4)	Canada	100	5,300	7,500,000	~50	75,000	~1,400
AgriProtein (Case study 2)	South Africa	250	9,000	8,000,000	~ 40	32,000	~900

[a] For case studies see chapter 6.

[b] Large part of the needed infrastructure was already available.

[c] Estimations by Diener et al. 2009a.

TABLE 17. LABOR REQUIREMENTS AND COSTS DEPENDING ON THE WASTE TREATMENT CAPACITY.

Facility[a]	Location	Capacity (tonne of waste day^{-1})	# full-time operators/ employees	Ratio # operators/capacity (operators tonne daily input^{-1})	Average wage (USD month^{-1})	Labor costs (USD year^{-1})	Ratio labor costs/capacity (USD tonne daily input^{-1})
Ento-Prise (Case study 3)	Ghana	0.33	1	3	160	1,920	~1,900
FORWARD (Case study 1)	Indonesia	Up to 3	3	1[b]	-	-	Less than 8,300[c]
Fictitious plant[d]	Costa Rica	3	5	1.7	~ 390	23,200	~7,700
Enterra Feed (Case study 4)	Canada	100	32	0.3		-	-
AgriProtein (Case study 2)	South Africa	250	90	0.4		-	-

[a] For case studies see chapter 6.

[b] Zurbrügg et al. (2018) established the ratio will reduce from 6 staff per tonne daily to 0.58 staff per tonne daily when the capacity of the plant is increased from 1 to 60 tonnes per day.

[c] Labor costs were estimated for a production of 1 tonne of waste day^{-1}. Economies of scale will normally cause the ratio to reduce for higher production capacities, i.e. between 1 and 5 tonne of waste day^{-1}.

[d] Estimations by Diener et al. 2009a; # = number.

Due to a higher level of automation, larger-scale BSF facilities require less staff to treat a given quantity of waste compared to smaller-scale BSF facility, as illustrated in Table 17. The labor requirement can also be calculated according to the biomass production. For example, Amatya (2008) assessed that based on the labor required for running an experimental BSF installation in Texas, labor costs for operating a commercial BSF facility could range from USD 540 to 2,100 kg of larvae^{-1} (dry matter basis), depending on the labor price and the larval development time. However, Amatya (2008) pointed out that the labor required for research is not representative of that at the commercial scale.

On the other hand, Caruso et al. (2013) estimated much lower labor costs, i.e. IDR 1,444 kg^{-1} of fresh larvae (i.e. USD 0.16 kg of fresh larvae^{-1} in 2010/11), accounting for approximately 30% of the total cost for running a pilot BSF facility in Indonesia. In comparison, in the cost estimations made by Diener et al. (2009a), costs related to labor represent 65% of the total running costs, and, if compared to the daily prepupal yield, amount to USD 0.42 kg of larvae^{-1} (DW). These values are summarized in Table 18 and compared to those of the Ento-Prise case study. Recently, Zurbrügg et al. (2018) established that for a plant processing 1 tonne per day of waste in Indonesia, labor costs were up to 45% of the plant running costs.

For many of the small scale plants, actual labor costs are not optimal and production capacity can be increased several times without impacting labour demands for parts of the process, such as the rearing unit (Zurbrügg et al. 2018).

Overall Running Costs

According to Pozzebon (2015), the operation costs associated with a BSF facility are low. This is illustrated by Caruso et al. (2013), who estimated that the variable costs for a pilot BSF facility in Indonesia are four times lower than fixed costs, while Diener et al. (2009a) and Popoff and Maquart (2016b) calculated yearly running costs that are almost 2.5 and 2 times lower than investment costs, respectively. For a small-scale plant in Indonesia, costs related to maintenance of equipment amount to 30% of the overall running cost (Zurbrügg et al. 2018). However, other variable costs such as electricity, water and chicken feed used to feed young larvae in the nursery attain about 12% of the total costs. Alvarez (2012), analyzing the economic viability of bench-scale BSF facility in Canada, estimated the water and energy costs, associated with the BSF process, at USD 0.3 m^{-2} year^{-1} for water, USD 4.8 m^{-2} year^{-1} for electricity and USD 37.2 m^{-2} year^{-1} for natural gas, amounting to a total of USD 42.3 m^{-2} year^{-1}. In this regard, the operation costs of a BSF facility significantly depend on the local climate, as breeding or rearing the BSF in unfavorable climatic conditions, such as in Northern countries, requires heating and potentially lighting to maintain the treatment running all year round, which results in significantly higher energy consumption costs (Cicková et al. 2015). Indeed, energy and water costs reported by studies conducted in tropical countries are much lower to those reported by Alvarez (2012), although a direct comparison will be difficult due to likely lower (pro-poor subsidized) consumption charges. For example, Diener et al. (2009a) estimated USD 0.45 m^{-2} year^{-1} for the total energy and water costs of a 1,100 m^2 BSF plant in Costa Rica, while Popoff and Maquart (2016b) reported a cost of USD 4.6 m^{-2} year^{-1} for the energy (gas and electricity) and water consumption of a 212 m^2 BSF plant in Ghana. Total running costs available in the literature are presented in Table 15 according to the daily waste treatment capacity.

Typically for Indonesia, Zurbrügg et al. (2018) established that operations related to the rearing unit could represent up to 31% of the plant running costs. The remaining treatment units would require 56% of the total operational costs for running. Indirect costs were estimated to 13% of the running costs.

5.1.3 Overall Economic Performance

The overall economic performance of a BSF waste treatment facility depends on various parameters such as the local climate and especially temperature and humidity levels, the quantity, type and quality (amount of inorganic material) of waste processed, the capital and operating costs associated with the facility, the revenues from the sales of larvae and the waste residue (depending on the cost of conventional animal feeds and fertilizers), and potentially from waste processing (e.g. the tipping fee) (Diener et al. 2009a; Campbell 2013; Dortmans et al. 2017). Similarly, Amatya (2008) identified two key parameters that influence the economic performance of a BSF system significantly,

TABLE 18. LABOR COSTS ACCORDING TO BIOMASS PRODUCTION AND TOTAL RUNNING COSTS.

Facility	Labor costs (USD kg of larvae^{-1})	Labor costs according to the total running costs (%)
Ento-Prise (case study 3)	0.11 (WW)	50
Fictitious plant in Costa Rica[a]	0.43 (DW)	65
Plant in Indonesia[b]	0.85 (DW)	30-45
	0.14 (WW)	30-45

[a] Estimations by Diener et al. 2009a; [b] estimations by Caruso et al. 2013 and Zurbrügg et al. 2018.

namely the dry matter conversion rate and the time required to convert the waste; these parameters being themselves affected by operating conditions (feedstock, temperature, humidity and so forth).

A few researchers tried to quantify the profit that a BSF facility could make. Alvarez (2012) established that, under specific assumptions and conditions, a BSF facility treating about 200 tonnes of food waste per year in Canada would earn approximately a profit of USD 50 day^{-1}, making it economically viable. However, some costs were not considered in the analysis and only the sales revenue from the larvae was considered. In addition, the climatic conditions in Canada being suboptimal for BSF breeding and rearing, operating costs related to energy consumption could be significantly reduced in tropical regions, which highlights the key impact of local climate on economic performance.

However, while energy costs associated with the BSF technology are much lower in tropical countries, the market demand for the products, especially the larvae-based feed ingredients, may be higher in Northern countries, where a large part of the animal production industry is located. Considering only the labor costs, the sales revenue from prepupae and the cost-savings on waste disposal, Amatya (2008) calculated the benefit for a BSF cow manure treatment facility in Texas as ranging from approximately USD 100 to 280 cow^{-1} year^{-1} depending on the market value of the prepupae, the manure management system and the size of the dairy. Still in the North American context, Newton et al. (2005) estimated that using BSF to manage chicken manure on site would yield a net profit of USD 25,000 per poultry house per year compared to conventional manure management. To improve the economic viability of BSF facilities in Northern countries, Alvarez (2012) identified potential enhancements, such as improving the building's energy efficiency and increasing the density of waste to be treated per unit area.

As for Southern countries, Agrawal et al. (2011), established that it was economically feasible to convert fecal sludge collected from pit latrines into biodiesel and poultry feed in Dar es Salaam, Tanzania. They recommended a step-wise approach consisting of (1) in the two first years, extracting the fat content of larvae in order to sell both the larvae oil to biodiesel producers and the defatted larvae as high-grade animal feed for poultry, and (2) in the third year, reinvesting the profit made in the first years in equipment to produce biodiesel. They estimated that the annual profit, from processing the waste of three latrines per day and selling the produced biodiesel and defatted larvae as high-grade poultry feed, could be USD 116,000.

5.2 Environmental Impact

Table 19 summarizes the main environmental benefits and adverse impacts associated with the BSF technology.

5.2.1 Environmental Benefits

Several environmental benefits associated with the BSF waste treatment method are documented in the literature. They include the potential substitution of unsustainable conventional feed sources by BSF larvae-based ingredients, the ability of the BSF process to reduce the pollution potential of the waste, the energy-related benefits and the odor reduction potential. These benefits are detailed in this section and summarized in Table 19.

TABLE 19. ENVIRONMENTAL BENEFITS AND NEGATIVE IMPACTS ASSOCIATED WITH A BSF FACILITY.

		Characteristics	References
Environmental benefits	Larvae as an alternative to unsustainable animal feed products	Producing insect-based meals from high-impacting waste streams or low-value food processing by-products is two to five times more environmentally friendly than manufacturing conventional feed products	Smetana et al. 2016
	Nutrient leakage reduction	Reduction of the pollution potential of waste by 50-60%	Newton et al. 2005; van Huis et al. 2013
	Energy-related benefits	The production of BSF larvae-based biodiesel exhibits a higher conversion efficiency (460 L tonne^{-1} of larvae, DW) and yields (50-30 10^6 L ha^{-1} year^{-1}) compared to common biodiesel feedstocks	FAO 2008; Li et al. 2011b; Zheng et al. 2012a, 2012b; Shikida et al. 2014
	Odor reduction	Odor reduction due to short processing time, reduction of bacterial activity, aerating and drying of the waste by larvae	Newton et al. 2005, 2008; Diener 2010; van Huis et al. 2013
Negative environmental impacts		Main adverse impacts: energy consumption for postprocessing of the products and waste transport	Salomone et al. 2017
Overall environmental performance		The impacts of processing 1 tonne of food waste into larvae protein for aquaculture and larvae oil for biodiesel production in Italy are estimated at: • 30.2 kg CO_2 equivalent of GWP; • 215.3 MJ of energy used; and • 0.661 m^2 of arable land used.	Salomone et al. 2017

Larvae as an Alternative to Unsustainable Feed Sources

Substituting conventional feed products used in the animal production industry could alleviate significant adverse impacts, associated with the production of fishmeal and soybean meal, which are largely documented in the literature, and are likely to become increasingly more severe as meat and fish consumption is soaring (Makkar et al. 2014; Lalander et al. 2015). For instance, 85% of the global soya production is used to manufacture soymeal, which is currently the main feed source for terrestrial animals, in order to sustain the growing livestock production in the Western hemisphere (Stamer 2015; Spranghers et al. 2017). As a result, the production of soybean meal puts pressure on land availability for human food production, especially in tropical regions (90 million hectares [ha] of land are used alone by the three main soya producers) and causes deforestation, thus impacting biodiversity and ecosystem services supported by tropical forests (Stamer 2015; Spranghers et al. 2017). In addition, soybean meal production relies on monoculture, which could threaten biodiversity, reduce soil fertility and deplete water resources (Stamer 2015). Similarly, 10% of global fish production is used to manufacture fishmeal, more than 90% of which is used in aquaculture, the fastest growing animal production sector (Papadoyianis 2007; van Huis 2013; van Huis et al. 2013; Stamer 2015). Therefore, as for soybean meal, Stamer (2015) pointed out that fishmeal production for aquaculture is increasingly competing with human food production. In addition, fishmeal production puts pressure on wild fish resources as it relies mainly on marine fisheries, especially small pelagic forage fish (Diener 2010; Tacon and Metian 2008; Lalander et al. 2015). Moreover, as 80% of global fishmeal production is carried out by only ten countries, the industry is associated with long-distance transport (the average transport distance for every tonne of fishmeal is 5,000 km) (Papadoyianis 2007).

The ability of the BSF to ensure a more sustainable feed production industry is supported by the findings of Smetana et al. (2016), who conducted a lifecycle assessment of insect production for feed manufacturing. By considering a wide range of environmental indicators, including Global Warming Potential (GWP), energy use and land use, they estimated that producing insect-based meals from high-impacting waste streams or low-value food processing by-products is two to five times more environmentally friendly than manufacturing conventional feed products. However, the overall environmental performance of producing feed ingredients from insects depends significantly on the substrate used to feed the insects. There is a trade-off between the efficiency of the bioconversion process, which depends on the nutritional quality of the diet and the environmental benefits related to the valorization of the feedstock. For instance, using a high-nutritional-quality diet, such as soybean meal or rye meal, to feed the larvae, yields a larger and higher quality insect biomass but the product is associated with high environmental impacts. On the other hand, using low quality substrates (e.g. chicken manure), for which the bioconversion process is less efficient, requires more resources and can thus result in adverse impacts that may cancel out the benefits from waste valorization. Overall, the substrates that proved the most beneficial were distillers' grains (a by-product from the brewery and alcohol industry) and municipal organic waste (Smetana et al. 2016).

Nutrient Leakage Reduction

BSF waste treatment has been reported to reduce the feedstock's nutrient content, thus decreasing the risk of nutrient leakage. Newton et al. (2005) reported that processing by BSF larvae reduced the nutrient concentrations in swine manure by 40 to 55%. Similarly, in an experimental BSF treatment unit for swine manure in Georgia, Newton et al. (2008) observed the following nutrient reduction rates in the manure processed by BSF larvae: 71% for nitrogen, 52% for phosphorus and potassium, and reduction performance ranging from 38 to 93% for other components such as aluminum, boron, cadmium, calcium, chromium, copper, iron, lead, magnesium, manganese, molybdenum, nickel, sodium, sulfur and zinc. For dairy manure, Myers et al. (2008) reported that BSF larvae reduced available phosphorus by 61-70% and nitrogen by 30-50%. Therefore, BSF technology can reduce the pollution potential by 50-60% or more (Newton et al. 2005; van Huis et al. 2013).

Energy-related Benefits

Use of the BSF technology may also imply energy savings. According to Newton et al. (2008), producing animal feed from BSF larvae requires much less energy than capturing and drying fish from the ocean to produce fishmeal. Besides, the BSF process yields energy-rich larvae which can be used to produce biodiesel (Li et al. 2011a; Zheng et al. 2012a, 2012b; Leong et al. 2016) and contribute to the sustainable production of energy. In addition, biodiesel produced from BSF larvae fed on inexpensive and abundant organic waste is an attractive alternative to conventional crop oil-based biodiesel, which relies on limited and expensive feedstock, and implies agricultural land competition and increased food price, thus threatening food security (Li et al. 2011a; Zheng et al. 2012a, 2012b).

To illustrate the potential of biodiesel production from BSF larvae, yields for BSF larvae's fat-based biodiesel are compared to those obtained for other feedstocks commonly used for biodiesel production (see Table 20).

TABLE 20. COMPARISON OF BIODIESEL YIELDS FOR DIFFERENT FEEDSTOCKS.

Feedstock	Conversion efficiency (L tonne of feedstock^{-1})	Biodiesel yield (L ha of land used^{-1} year^{-1})	References
Oil extracted from BSF larvae	460^{a}	50.10^{6}-230.10^{6b}	Diener et al. 2009a; Popoff and Maquart 2016b
Soybean	205	491-552	FAO 2008
Oil palm	230	4,092-4,736	FAO 2008
Rapeseed oil	-	1,320	Shikida et al. 2014

[a] Average value calculated from the values reported in Table 13.

[b] Values calculated based on the space area and daily larval yield of a fictitious BSF plant in Costa Rica and an existing pilot plant in Ghana.

As shown in Table 20, the average biodiesel conversion efficiency for BSF larvae (460 L tonne of larvae^{-1}, DW) is at least twice higher than that for soybean (205 L tonne^{-1}) and oil palm (230 L tonne^{-1}) (FAO 2008). Moreover, producing biodiesel from BSF larvae is much more efficient in terms of land use. For example, producing 1 L of biodiesel from BSL larvae requires on average about 270,000 times less space compared to soybean or 30,000 times compared to oil palm.

Odor Reduction

The BSF process reduces and sometimes even eliminates the foul odor from decomposing organic matter thanks to the short processing time, due to high larval density and the voracious appetite of the larvae, the reduction of bacterial activity, as well as the larvae's aerating and drying of the waste (Newton et al. 2005, 2008; Diener 2010; van Huis et al. 2013).

5.2.2 Adverse Environmental Impacts

According to Salomone et al. (2017), the main adverse impacts associated with the BSF technology are attributable to energy consumption for postprocessing the products, and especially drying the larvae, and waste transport, which, however, is not an impact specific to BSF waste treatment. Regarding greenhouse gas emissions, Perednia et al. (2017) established that about 28.5% of the carbon contained in the feedstock is lost to the atmosphere in the form of CO_2 through the bioconversion process by the BSF. However, in comparison, aerobic composting results in 70% more direct CO_2 emissions into the atmosphere. This is because, unlike the microorganisms involved in aerobic composting, BSF larvae are able to incorporate on average 41% of the carbon into their body mass in the form of protein, lipids and chitin (Perednia et al. 2017). In addition, BSF larvae grown under aerobic conditions generate negligible amounts of CH_4 (Perednia et al. 2017). Adverse environmental impacts associated with the BSF process are summarized in Table 19.

5.2.3 Overall Environmental Performance

Very few studies have analyzed the overall environmental performance of the BSF process. Salomone et al. (2017) conducted a lifecycle assessment to assess the environmental impacts of a BSF pilot plant in Italy processing food waste into compost, larvae protein for aquaculture and larvae lipids for biodiesel production. They estimated the impacts of 1 tonne of treated food waste at 30.2 kg CO_2 equivalent in terms of GWP, 215.3 MJ in terms of energy use and 0.661 m^2 of arable land in terms of land use (see Table 19). They established that the postprocessing step, for producing animal feed and compost, causes the most impacts, followed by the transport phase. They identified that the most significant impact associated with BSF technology is energy consumption related to the drying process for the larvae. In addition, by comparing these results with those obtained when alternative raw materials are used for fish feed (soybean meal) or biodiesel production (rapeseed), they found that land use is the most important benefit of BSF waste treatment, while energy use is the main adverse impact. However, they pointed out that as pressure on agricultural land availability is increasing, the minimal land use required to produce animal feed and biodiesel from BSF larvae may become an aspect much more important than GWP and energy use. Comparison data are presented in Table 21. Regarding compost, Salomone et al. (2017) reported that using BSF fertilizer instead of nitrogen fertilizer is associated with significant environmental benefits, mainly in terms of GWP.

TABLE 21. COMPARISON OF DRIED LARVAE WITH ALTERNATIVE FEEDSTOCKS FOR FEED AND BIODIESEL PRODUCTION IN TERMS OF ENVIRONMENTAL IMPACTS.

	Fish feed		Biodiesel	
	1 kg protein (dried larvae)	1 kg protein (soybean meal)	1 kg lipids (dried larvae)	1 kg lipids (rapeseed)
GWP (kg CO_2 eq.)	2.1	1.7	2.9	2.7
Energy use (MJ)	15.1	4.1	20.8	11
Land use (m^2 of arable land)	0.05	8.7	0.06	6.5

Source: Salomone et al. 2017.

Komakech et al. (2015) also compared, from an environmental perspective, different organic waste treatment options, namely anaerobic digestion, composting, vermicomposting and BSF treatment, in the context of Sub-Saharan African cities. They found that BSF treatment did not perform as well as the anaerobic digestion system, which exhibits the highest environmental performance for all impacts investigated (energy use, GWP and eutrophication potential). However, the impacts related to the substitution of fish by BSF larvae in animal feed production, which may constitute one of the major environmental advantages of BSF technology over other treatment methods, were not all considered by Komakech et al. (2015). In addition, knowledge on BSF technology is not as advanced as that on other valorization options, so results regarding BSF waste treatment may not be as reliable. In any case, the environmental performance of a BSF plant depends on several factors, including the origin and nature of the waste used to feed the larvae, end uses of the products and local climate (Ponce Jara 2015; Smetana et al. 2016).

5.3 Legal Aspects

The main legal issue regarding the BSF technology concerns the use of insects as feed ingredients in the animal production industry. Many countries do not have any regulation regarding animal feeding with insect protein (Caruso et al. 2013; van Huis et al. 2013; Cicková et al. 2015). According to van Huis et al. (2013), the lack of clear legislation and standards regulating the use of insects as animal feed constitutes one of the most important barriers to industrial development of insect rearing for feed production in developed countries. On the other hand, in developing countries, in the absence of stringent standards regarding animal production, the use of insect protein to feed animals is often tolerated (van Huis et al. 2013). For example, BSF larvae-based feed ingredients produced industrially by AgriProtein in South Africa (see case study 2) have been approved for sale in South Africa but not yet in Europe (Pozzebon 2015). Table 22 provides an overview of the current legislation pertaining to the use of BSF larvae as animal feed in different parts of the world.

TABLE 22. LEGISLATION REGARDING THE USE OF BSF LARVAE AS ANIMAL FEED IN DIFFERENT PARTS OF THE WORLD.

Context	Legislation regarding the use of BSF larvae proteins as animal feed	References
EU	The use of feed ingredients derived from BSF larvae has been recently authorized in aquaculture, but most conventional waste streams are prohibited for use as feedstock to rear the larvae. The use of BSF larvae to feed livestock animals is still banned	Caruso et al. 2013; van Huis et al. 2013; Cicková et al. 2015; Leung 2016, 2017; FEFAC 2017; IPIFF 2017
North America	Some BSF larvae-based feed ingredients have been approved as feed for certain fish and poultry species in the USA and Canada	
Developing countries	The use of insect protein to feed animals is often tolerated, resulting in fewer legal barriers	

In North America, some commercial BSF ventures, such as Enterra Feed in Canada (see case study 4), have succeeded in getting approval from the Canadian Food Inspection Agency (CFIA) and the Food and Drug Administration (FDA) in the USA, for the use of their larvae-based feed products as feed for specific species of fish and poultry (Leung 2016, 2017). In the EU, the use of insect protein to feed animal so far has been prohibited by the 'feed ban rules' in the so-called 'TSE Regulation' (Article 7 and Annex IV of Regulation 999/2001), which banned the use of animal-derived proteins to be used as feed in animal production. However, in view of the promising potential of insect proteins to replace unsustainable conventional feed sources in aquaculture, the EU legislation has recently evolved. The European Commission adopted the Commission Regulation (EU) 2017/893, which partially uplifts the feed ban rules by authorizing, from July 2017, the use of processed proteins derived from seven insect species, including the BSF, in aquaculture. However, insects reared for feed production are considered as farmed animals according to the EC Regulation 1069/2009, which implies that they are governed by the 'general EU feed rules' and thus can only be fed with materials authorized for animal feed. As a result, the EU regulation prohibits feeding insects, to be used as animal feed, with manure and catering waste for example. Therefore, most conventional waste streams are not considered as suitable substrates by the EU, which constitutes a legal barrier to selling BSF larvae used in organic waste treatment. In addition, the use of processed insect protein to feed livestock animals is still prohibited by the EU regulation (Cicková et al. 2015; FEFAC 2017; IPIFF 2017).

Legal limitations are mainly due to limited knowledge and data regarding toxicity, allergenicity and diseases' transferability associated with insects used as animal feed (van der Spiegel et al. 2013; European Food Safety Authority 2015; Smetana et al. 2016). Some initiatives to assess the safety of feeding animals with fly larvae proteins derived from the conversion of organic waste are ongoing, to provide more scientific evidence for policy-makers (PROteINSECT 2016).

5.4 Social Aspects

Table 23 highlights the main social issues and benefits associated with the BSF technology.

5.4.1 Public Health

One of the major benefits of BSF technology reported in the literature relates to public health. As a treatment solution for organic waste, BSF technology contributes to reducing the occurrence of disease caused by unmanaged organic waste. But most importantly, the literature highlights that the BSF is a non-pest insect which does not constitute a vector of diseases, making it harmless to human health. This is because the adult BSF does not possess a stinger or a mouth to bite. In addition, as the adult fly does not feed, it does not hop from one food source to another and is not attracted by human habitats. However, exceptional cases of myiasis caused by the consumption of ripe and unwashed fruits where BSF larvae were present were reported by Adler and Brancato (1995), Lee et al. (1995) and González and Oliva (2009) in tropical regions. Furthermore, the BSF repels other common fly species, such as houseflies, which are well-known vectors of diseases, especially in developing countries. Specifically, the BSF is reported to inhibit housefly oviposition by emitting a characteristic odor, which is not offensive to humans but drives away other fly species (Furman et al. 1959; Sheppard 1983; Bradley and Sheppard 1984; Sheppard et al. 1994, 1998; Newton et al. 1995; Diener 2010; Olivier et al. 2011; Caruso et al. 2013; van Huis et al. 2013; Oliveira et al. 2015). Finally, studies have shown that the BSF valorization process reduces some pathogens in the organic waste, as discussed previously.

On the other hand, Cicková et al. (2015) pointed out that the release of volatile by-products and noxious gases, especially ammonia, during the bioconversion of organic waste by BSF larvae could constitute a health hazard for the staff working at BSF waste treatment facilities. In this regard, Lalander et al. (2015) suggested that large-scale facilities could keep ammonia emissions low by condensing the outgoing air. Benefits and adverse impacts associated with the BSF technology that relate to public health are summarized in Table 23.

5.4.2 Social Benefits

The nutrients recovered through the BSF process can be used by local farmers as fertilizer to increase productivity which can improve their livelihoods. Such treatment for organic waste can also create employment opportunities for vulnerable people including youth, women or marginalized people (Diener et al. 2011; Nikiema et al. 2014). In addition, the BSF technology for organic waste valorization could create new niches for small entrepreneurs in low- and middle-income countries. Diener et al. (2015a) indicated that the BSF technology can be interesting for a wide range of entrepreneurs all over the world such as a public toilet entrepreneur in a bustling urban center of an African city, a medium-scale pig-producer operating in a rural area of North America or an organic waste manager in an Asian food market. By using BSF technology to generate additional revenues from the sales of the energy-rich larvae, farmers and small entrepreneurs in developing countries could enhance their economic resilience to market fluctuations and natural hazards (Diener et al. 2011). Some authors have highlighted that using BSF larvae as animal feed and the waste residue as an organic fertilizer can favor food security (Makkar et al. 2014; van Huis et al. 2013).

5.4.3 Social Acceptance

Insects are usually considered a nuisance. However, some cultures acknowledge the benefits of insects, especially as a source of protein (Barry 2004; van Huis et al. 2013). To promote social acceptance of the BSF technology, Barry (2004) designed educational material, including a children's book and fifth grade curriculum in the USA. In addition, the EU-funded project PROteINSECT conducted a consumer perception survey in which 2,400 consumers from over 70 countries participated, that shows a high level of social acceptance toward the use of insects as a protein source in animal feed (PROteINSECT 2016). About 70% of the respondents considered that insects are a suitable source of proteins to feed animals, including fish, and 70% of them also indicated that they would be willing to eat fish or meat from animals fed with insect-based ingredients. Popoff et al. (2017) also investigated the attitude of both consumers and producers toward the use of insect-based ingredients to feed Scottish salmon in the UK. They observed that only 10% of the 180 respondents were against including insect proteins in salmon feed. In addition, 75% of the respondents claimed that feeding salmon with insect ingredients would not affect their willingness to buy the fish. However, they were told that the insects were reared on vegetable waste. Survey results may be different for insect reared on animal or human waste. On the other hand, supermarket food waste and vegetable waste were the preferred substrates for feeding the larvae. The producers interviewed also expressed their interest in using insect-based feed ingredients as long as they are proven to be safe and can be supplied reliably (Popoff et al. 2017).

In Table 24, the BSF waste treatment method is compared to other organic waste valorization techniques, such as composting, anaerobic digestion and vermicomposting.

TABLE 23. SOCIAL ISSUES AND BENEFITS ASSOCIATED WITH THE BSF TECHNOLOGY.

Aspect	Description	References
Public health	The BSF is a non-pest insect which does not constitute a vector of disease. BSF repel other common fly species, such as house flies. Exceptional cases of myasis caused by BSF larvae have been reported in tropical countries. BSF larvae reduce some pathogens in the waste. Release of volatile by-products and noxious gases during the bioconversion of organic waste by BSF larvae could constitute a health hazard for the staff working at BSF facilities.	Furman et al. 1959; Sheppard 1983; Bradley and Sheppard 1984; Sheppard et al. 1994; Adler and Brancato 1995; Lee et al. 1995; Newton et al. 1995; Sheppard et al. 1998; González and Oliva 2009; Diener 2010; Olivier et al. 2011; Caruso et al. 2013; van Huis et al. 2013; Cicková et al. 2015; Oliveira et al. 2015
Social benefits	BSF technology could provide livelihood opportunities for farmers and entrepreneurs all over the world, and especially in developing countries. By yielding protein-rich larvae that can be used as animal feed and a waste residue that can act as a fertilizer, BSF technology could contribute to food security.	Diener et al. 2011, 2015a; Makkar et al. 2014; van Huis et al. 2013
Social acceptance	According to several studies, consumers seem to have a positive attitude towards the inclusion of BSF larvae-based ingredients in the diet of farmed animals and are willing to eat meat from animals that are fed with BSF larvae ingredients. However, consumer acceptance may depend on the type of waste used to feed the larvae.	FERA 2016; PROteINSECT 2016; Popoff et al. 2017

TABLE 24. COMPARISON BETWEEN THE BSF TECHNOLOGY AND OTHER ORGANIC WASTE TREATMENT OPTIONS.

Aspect	The BSF treatment compared to other organic valorization techniques
Feedstock	Besides materials exhibiting a high lignocellulosic content, most organic waste can be processed through the BSF technology. In addition, nutrient balance and pH are not essential. Thus, the BSF technology is more flexible in terms of input compared to anaerobic digestion and vermicomposting, for which feedstocks with a narrower range of C/N balance are suitable.
Resource requirements	When using vertical stacking, the BSF process requires little space (e.g. ~150 m^2 $tonne^{-1}$ of daily input in medium-scale facilities and 40-50 m^2 $tonne^{-1}$ of daily input in large-scale facilities) compared to composting (200-250 m^2 $tonne^{-1}$ of daily input) and vermicomposting (800 m^2 $tonne^{-1}$ of daily input or 200 m^2 $tonne^{-1}$ of daily input with vertical stacking). Energy requirements depend on climatic conditions. In Northern countries, the process may be relatively energy-consuming compared to other organic waste treatments. On the other hand, in tropical climates, no environmental control and thus much less energy is required. However, drying the larvae, depending on the drying technology used, may significantly increase the energy requirements of the BSF waste treatment.
Processing time	Waste processing time by the BSF is very short (10 to 14 days, based on the case studies) compared to composting (> 90 days for mature compost), vermicomposting (>45 to 60 days) and anaerobic digestion (30 days). However, the waste residue obtained may need to undergo a maturation phase.
Hygienization	Like vermicomposting and anaerobic digestion, the BSF treatment does not allow complete inactivation of pathogens, while composting does thanks to high temperatures inside the compost piles.
Emissions	Compared to composting, the BSF bioconversion process results in 70% less CO_2 emissions. In addition, there is no risk of CH_4 leakages, like there is for anaerobic digestion. Finally, the BSF process is not odorous as BSF larvae reduce and sometimes even eliminate the foul odor from decomposing organic matter.
Skills requirement	Like composting and vermicomposting, the BSF treatment only requires simple labor skills, while anaerobic digestion entails technical skills and trained technicians.
Products (value and yield)	An advantage of the BSF process is that it yields two valuable products. In addition, larvae-derived feed products are associated with a potential significant market demand from the animal production industry. Studies conducted in different contexts estimated that larvae-based feed products could exhibit a market value comparable or slightly lower than biogas, but significantly higher than compost. Hence, the BSF waste treatment may have a greater potential to incentivize waste management, compared to composting.
Investment costs	Compared to anaerobic digestion, the BSF waste treatment is a low-cost technology.
Regulatory hurdles	Regulatory hurdles related to the use of insect-based feeds in animal production are probably the main drawback associated with the BSF technology, while regulation is a less important issue for other treatment methods.
Maturity of the technology	Compared to the other treatment methods, the BSF technology is relatively immature and cases of implementation are still scarce.

Sources: Based on Diener et al. 2014; Komakech et al. 2015; Lalander et al. 2017; Lohri et al. 2017; Perednia et al. 2017; and data from the case studies.

6. IMPLEMENTATION OF BSF TECHNOLOGIES: CASE STUDIES

6.1 Overview

Nowadays, two main trends regarding the implementation of the BSF technology can be distinguished. On the one hand, large-scale industrial facilities, processing up to several hundreds of tonnes of waste daily and producing dozens of tonnes of larvae-based feed ingredients, are already being operated in South Africa, Canada, the USA, the Netherlands and China. These facilities focus primarily on the production of proteins for the animal feed industry, taking advantage of potentially great market opportunities (Diener et al. 2015a). The examples of AgriProtein in South Africa and Enterra Feed in Canada are presented in this section. On the other hand, many small-scale BSF systems have been implemented at the household level by enthusiastic individuals primarily motivated by the waste treatment aspect. In this regard, several blogs and discussion forums, where experiences and designs are shared, can be found on the Internet (e.g. blacksoldierflyblog.com, blacksoldierflyfarming.com). In the middle of the spectrum, medium-scale BSF facilities treating hundreds of kilograms to 10 tonnes of waste daily are very scarce (Diener et al. 2015a; Zurbrügg et al. 2018). In addition, the few that do exist have been built as part of research projects, like FORWARD in Indonesia and Ento-Prise in Ghana (cases presented in this section) and have not yet succeeded to reach profitability (Murray 2016; B. Dortmans, pers. comm., September 28, 2017). To bridge this gap and ensure both an efficient waste management and profitable protein production system, Diener et al. (2015a) suggested a semicentralized organization, which combines the advantages of centralized large-scale facilities focusing on protein production and the benefits of decentralized waste management systems, consisting of a centralized BSF breeding, rearing and refinery facility working with a network of decentralized waste treatment units located near waste generation sources. A similar organization was suggested by Campbell (2013) to make the BSF technology more accessible for on-farm manure management by livestock farmers. Table 25 provides an overview of the case studies developed as part of this analysis.

6.2 Case Study 1: FORWARD

From Organic Waste to Recycling for Development (FORWARD) is a non-profit research and development (R&D) project, led by the Swiss Federal Institute of Aquatic Science and Technology (Eawag). It is funded by SECO, the Swiss State Secretariat for Economic Affairs, under a framework agreement with the Indonesian Ministry of Public Works & Housing (PU-PeRa). This initiative has a focus on integrated strategies and technologies for the management of municipal organic solid waste in medium-sized cities of Indonesia. It investigates local market opportunities for municipal organic solid waste valorization in medium-sized cities in Indonesia. As part of this project, a pilot BSF waste treatment plant was constructed to act as an applied research facility, as well as a showcase and training center. It is now operating at Puspa Agro, the wholesale market of Sidoarjo in East Java (Table 26). FORWARD was supported by another research project - SPROUT – which focused on ways to optimize hygienic aspects, design and operation of BSF waste treatment units, quality of products (feed and fertilizer), post-harvest processing regarding feed quality and product safety, business models for BSF waste processing. SPROUT also attempted to evaluate the environmental impact of BSF waste processing compared to other biological treatment options. SPROUT is funded via the EU-program ECO-INNOVERA, the Swedish Research Council Formas, the Swiss Federal Office for the Environment FOEN, and Pacovis AG (Zurbrügg et al. 2018).

6.2.1 Context

Indonesia is the fourth most populous country in the world and the largest economy in Southeast Asia. It is a middle-income country exhibiting impressive economic growth. The operation site of this initiative is in Sidoarjo located on Java, the most densely populated island in the world. It is a medium-size city, with 2 million inhabitants, located in the metropolitan area of Surabaya, the second largest city in Indonesia. In Sidoarjo, the daily household solid waste generation for 2013 amounted to almost 1,600 tonnes, less than 25% of which was collected. In addition, waste generation is expected to increase as Sidoarjo's population is rapidly growing. In Indonesia, the organic waste fraction accounts for about 60% of the total municipal solid waste generated.

In Indonesia, municipal solid waste management is regulated at the national level by the 18/2008 law, which states reduce, recovery and recycling objectives. In addition, there are no legal barriers for feeding processed BSF larvae to animals in Indonesia. Actually, the Indonesian government often regulates animal feed imports to foster the local production of protein and there is a growing demand for locally produced protein to expand the Indonesian animal production industry (aquaculture and meat production), which is currently underdeveloped. Today, Indonesia imports most of the feed used in animal production (80% of soybean meal and 55% of fishmeal), which accounts for 80% of the total production cost. Regarding compost, a market analysis showed that it could be sold on the home gardener market, but it is a highly competitive market.

6.2.2 Technology and Process

Production characteristics of the FORWARD BSF facility are summarized in Table 26.

TABLE 25. OVERVIEW OF AND COMPARISON BETWEEN THE CASE STUDIES DOCUMENTED.

Case study	FORWARD	AgriProtein	Ento-Prise	Enterra Feed
Location	Indonesia	South Africa	Ghana	Canada
Context	Lower middle-income country, tropical climate	Upper middle-income country, temperate climate	Lower middle-income country, tropical climate	High-income country, temperate climate
Case type	Research project	Commercial venture	Research project	Commercial venture
Scale	Medium scale	Large scale	Medium scale	Large scale
Waste input type	Market waste	Food industry, restaurant and municipal organic wastes	Market waste	Preconsumer food waste
Waste-processing capacity	3 tonnes of waste day^{-1}	250 tonnes of waste day^{-1}	0.33 tonnes of waste day^{-1}	100 tonnes of waste day^{-1}
Products	Whole and dried larvae, biofertilizer and BSF breeding starter kit	Dried and defatted BSF larvae, larvae oil and biofertilizer	Dried larvae and biofertilizer	Whole dried larvae, larvae meal, larvae oil and biofertilizer
Production capacity	0.2 tonne (WW) of grown larvae day^{-1}	7 tonnes of insect meal, 3 tonnes of oil and 20 tonnes of biofertilizer day^{-1}	About 0.006 tonnes of dried larvae day^{-1} and 0.075 tonnes of biofertilizer day^{-1}	7 tonnes day^{-1} of protein and oil feed ingredients and 8 tonnes day^{-1} of biofertilizer
Facility area	424 m^2 (~140 m^2 to process 1 tonne day^{-1})	9,000 m^2 (~ 40 m^2 to process 1 tonne day^{-1})	212 m^2 (~640 m^2 to process 1 tonne day^{-1})	5,300 m^2 (~50 m^2 to process 1 tonne day^{-1})
Number of operators /employees	3 operators	90 employees (0.4 employees to process 1 tonne day^{-1})	1 operator (3 operators to process 1 tonne day^{-1})	32 employees (0.3 employees to process 1 tonne day^{-1})
Construction cost of the facility	Not available (already existing facility)	USD 8 million (~USD 32,000 tonne^{-1} of daily waste treatment capacity)	USD 6,090 (~USD 20,000 tonne^{-1} of daily waste treatment capacity)	USD 7.5 million (~USD 75,000 tonne^{-1} of daily waste treatment capacity)
Waste processing time	12 days	10 days	10 days	14 days
References for each case study	Bucher and Peterhans 2016; Verstappen et al. 2016; Wijaya 2016; B Dortmans, pers. comm., September 28, 2017; Dortmans et al. 2017; Eawag 2017a, 2017b; World Bank 2017b; Zurbrügg et al. 2018	Heffernan 2013; Iwuoha 2014; Pozzebon 2015; Burwood-Taylor 2016; van Jaarsveldt 2016; AgriProtein 2017a, 2017b, 2017c, 2017d, 2017e, 2017f, 2017g; Grant-Marshall 2017; World Bank 2017a, 2017c	Devic et al. 2014, 2017; Impraim et al. 2014; Adeku 2015; Maquart et al. 2015; Miezah et al. 2015; Murray and Newton 2015; AFO 2016; FAO 2016; Murray 2016; Popoff and Maquart 2016a, 2016b; E.K. Boadu, pers. comm, October 16, 2017; P.O. Maquart, pers. comm., October 26, 2017; Quilliam et al. 2017	Enterra 2013, 2015, 2016a, 2016b, 2017a, 2017b, 2017c, 2017d; Marchant 2015; NZWC 2015; Leung 2016, 2017; Nature 2016; Tetra Tech 2016; RCBC 2017

TABLE 26. THE FORWARD BSF FACILITY IN EAST JAVA: PRODUCTION CHARACTERISTICS.

	General
Waste input type	Market waste (mostly fruit and vegetable)
Waste-processing capacity	3 tonnes of organic waste day^{-1}
Products	Animal feed, compost and starter kits
Production capacity	Unknown
Status of validation	Proof of concept
	Preprocessing
Preprocessing techniques	Rough sorting, waste particle size reduction through shredding, weighting and, if required, dewatering via a passive dewatering system consisting of a bucket in which a cloth bag filled with the waste is placed
Feedstock characteristics after preprocessing	Moisture content of the waste: 75% (WW); particle size: 0.5-1 cm
	Waste treatment
Configuration	Reactors consist of individual trays that can be handled manually by operators. To save space, they are stacked upon each other and ventilation frames are placed in between levels to allow air flow
Larval density	4 larvae cm^{-2}
Feeding rate	125 mg^{-1} larva^{-1} day (WW)
Feeding regime	Incremental: 3 feedings of equal amounts on the 1st, 5th and 8th day of treatment
Waste load	5 kg m^{-2}
Larval feeding period	12 days
	Harvesting and post-treatment
Harvesting	Manual harvesting using flat screens, collection buckets and strainer spoons
Sanitization	Larvae placed in boiling water for 1 minute
Postprocessing	Larvae: sun drying; waste residue: composting
	Rearing
Egg production	Adult flies bred in netted cages and provided with oviposition media which are collected each day and placed above a container filled with a mixture of chicken feed and water to hatch
Young larvae production	Neonate larvae kept 5 days in the nursery before being used for waste treatment. At full capacity, about 2 million young larvae can be produced daily
Colony perpetuation	1% of young larvae are kept in the rearing unit. They are fed a mixture of chicken feed and water for 2.5 weeks. A self-harvesting system is used to collect prepupae which are placed in dark cages to pupate. Emerged flies are transferred to the netted cages by connecting them to the dark cages and using artificial light

Note: Data were collected October - November 2017

6.2.3 Economic Viability and Impacts

The research project was initially funded by SECO, but information on the amount of funding and the proportion used for the BSF facility was not available. Today, the plant does not rely on external funding to sustain its activity. However, the major source of revenues comes from the provision of training packages to the numerous people who are eager to learn about the BSF technology. Without the training activity, running of the plant would not be economically viable due to insufficient supply of waste. Currently, it receives only 0.3-0.5 tonnes of waste day^{-1}, which is not enough to ensure the profitability of the operation. Unfortunately, by operating under capacity, the waste treatment facility may result in more environmental detriments than environmental benefits. The project has generated local employment. At full capacity, three full-time workers would be required to operate the BSF facility.

The key success factors are linked to institutional support both at the national and local levels, adequate funding, partnerships with local researchers, a climate favorable to BSF rearing, relatively high market value and market demand for insect protein as well as a conducive legislative and policy environment.

6.3 Case Study 2: AgriProtein

AgriProtein is the world's first industrial BSF-based feed producer and currently the world's largest BSF company. It was founded in 2008 in South Africa. After two years of R&D, a BSF pilot plant was built at Elsenburg in 2010. Then, in 2014, the first commercial scale facility of 9,000 m^2 was built in Philippi (Cape Town). AgriProtein has now raised funds to build a second commercial BSF plant in South Africa. In addition, AgriProtein aims to mainstream its technology by building 100 BSF plants, each processing 250 tonnes of waste day^{-1}, by 2024 and 200 by 2027, in North America, Europe, Australia, Asia and the Middle East.

6.3.1 Context

South Africa is one of the largest economies in Africa. Since its transition to democracy in the mid-1990s, the country has made significant progress toward improving the well-being of its population. However, in recent years, progress has slowed. The country still faces high unemployment rates, especially among youth (half of whom are unemployed), making the creation of job and entrepreneurial opportunities a priority. South Africa is still a dual economy exhibiting one of the highest inequality rates in the world. In South Africa, 90% of the solid waste generated is landfilled. Yet, rapid urbanization has resulted in limited land availability for landfills, making it necessary to divert waste from landfills, especially the organic fraction, which represents 40% of the waste generated in South Africa. This has been captured in South African policies via, for example, the Waste Act 2008 (Act 59 of 2008) which promotes waste diversion from landfill through waste avoidance, reduction, reuse, recycling and recovery.

On the other hand, there is a significant need for locally produced animal feed products, especially for the rapidly growing South African aquaculture sector. However, Africa produces less than 1% of the animal feed products manufactured globally. As this is not sufficient to meet domestic demand, the African animal production sector relies heavily on imported feed from the USA, Europe, South America and Asia.

6.3.2 Technology and Process

Production characteristics of the AgriProtein facility are summarized in Table 27.

TABLE 27. THE AGRIPROTEIN FACILITY IN CAPE TOWN: PRODUCTION CHARACTERISTICS.

	General
Waste input type	Food industry, restaurant and municipal organic wastes (including animal manure, slaughterhouse waste, food waste, etc.)
Waste-processing capacity	250 tonnes of organic waste daily
Products	Dried and defatted BSF larvae, oil extracted from whole dried larvae and biofertilizer
Production capacity	7 tonnes of larvae meal, 3 tonnes of oil and 20 tonnes of biofertilizer daily
Status of validation	Commercially proven
	Preprocessing
Preprocessing techniques	Sorting, blending, crushing, pumping and circulating the paste obtained, so-called 'LarvaeLunch'
	Waste treatment
Configuration	Waste processed in large trays stacked vertically and in controlled climatic conditions
Larval feeding period	10 days
	Harvesting and post-treatment techniques
Harvesting	Unknown
Sanitization	Unknown
Postprocessing	Unknown
	Rearing
Egg production	Egg production is ensured by 8.5 billion flies bred in netted cages. To optimize production, AgriProtein uses specific light wavelengths, fly sexing techniques and selects the most productive male and female flies
Colony perpetuation	Rearing techniques used for the other lifecycle stages are not specified

Note: Data were collected October - November 2017

6.3.3 Economic Viability and Impacts

AgriProtein received funding from the Bill and Melinda Gates Foundation. For R&D, it has also partnered with both local and international universities. Finally, it has corporate partners, such as Christof Industries which assisted AgriProtein with upgrading its BSF plants in Cape Town and is now in charge of mainstreaming AgriProtein's technology by building new BSF plants worldwide (an Engineering, Procurement & Construction [EPC] partner) and developing Specialised Aquatic Feeds for testing its feed ingredients.

AgriProtein provides jobs (90 full-time staff). It has created employment, especially in Philippi, a disadvantaged district of Cape Town, where it launched its first commercial scale plant. To provide more jobs, AgriProtein deliberately limited automation in some units of the Philippi facility. In addition, 60% of the plant staff are women.

No information is available regarding AgriProtein's viability, but as the company is currently expanding by building new facilities, it can be supposed that its business model is viable. Building a 250-tonnes-of-waste-per-day BSF facility costs USD 8 million but as operational costs could be relatively low, investment could be amortized quickly. However, data regarding operational costs are not available. AgriProtein products have been approved for sale in South Africa but not yet in Europe due to unfavorable regulations.

Processing 250 tonnes of waste a day allows the diversion of 90,000 tonnes of organic waste per year from landfill sites. Using 1 tonne of larvae meal enables 3 tonnes of wild fish to remain in the ocean. In addition, AgriProtein estimated that producing 1 tonne of larvae meal enables an environmental cost saving of USD 2,550 in terms of fossil fuel consumption, wild fish resource depletion and carbon emissions, compared to fishmeal. However, as AgriProtein processes a wide range of organic waste from multiple sources, the risk of contamination of larvae products is higher.

The key success factors are linked to the significant initial R&D efforts, progressive upscaling from the laboratory scale to the industrial scale and to accessing funding opportunities and networks of both academic and corporate partners.

6.4 Case Study 3: Ento-Prise

Ento-Prise is a research project supported by the Agricultural Technology Transfer Research Challenge Fund and linked to PROteINSECT, an EU-funded project involving 12 partners from seven countries and coordinated by the Food and Environment Research Agency (FERA) in the United Kingdom. It aims at establishing a commercial BSF bioconversion system for organic waste to benefit smallholder farmers in Ghana. As part of the Ento-Prise project, carried out from 2014 to 2016, a BSF experimental pilot facility was initiated in Ashaiman (Greater Accra) at the Ghana Irrigation Development Authority site and then a demonstration plant was built in Adenta (Greater Accra) at the Animal Research Institute site of the Council of Scientific and Industrial Research.

6.4.1 Context

Ghana, as a rapidly growing and urbanizing middle-income country in West Africa, faces several major challenges, including:

- Improving its waste management system: In Ghana's main cities, 20 to 40% of municipal solid waste is not collected, while 60% of the municipal waste is of organic nature;
- Improving its agricultural productivity to meet the growing food demand: The development of the agriculture sector (including crop farming, livestock breeding and aquaculture) is constrained by the limited availability of affordable farming inputs; and
- Providing livelihood opportunities: More than one quarter of the population still lives under the poverty line of USD 1.25 day^{-1}.

There is an important market demand from the growing Ghanaian aquaculture sector for locally produced feed ingredients to replace expensive imported feed products, which account for up to 60% of the production cost of the sector. The animal production industry in Ghana is regulated by the Food and Drugs Law from 1992 (PNDCL 305B), but this legislation does not include any law on animal feed. Therefore, no law excludes the use of fly larvae to feed animals in Ghana. The 1999 Environmental Sanitation Policy revised in 2010 states objectives related to waste reduction, reuse, recycling and recovery. In addition, farmers in peri-urban areas, mainly growing fruits and vegetables to supply urban markets, need local biofertilizer to increase crop yields and enhance the fertility of depleted soil.

6.4.2 Technology and Process

Production characteristics of the Ento-Prise project are summarized in Table 28.

TABLE 28. THE ENTO-PRISE PROJECT IN GREATER ACCRA: PRODUCTION CHARACTERISTICS.

	General
Waste input type	Fruit and vegetable waste
Waste-processing capacity	About 0.3 tonnes of waste daily
Products	Dried larvae and compost
Production capacity	About 0.006 tonnes of dried larvae daily (0.038 tonnes of fresh larvae) and 0.075 tonnes of compost daily
Status of validation	Proof of concept
	Preprocessing
Preprocessing techniques	Sorting, blending, crushing, pumping and circulating the paste obtained, so-called 'LarvaeLunch'
	Waste treatment
Configuration	2 x 2 m concrete basins fitted with a drainage system
Larval feeding period	10 days
	Harvesting and post-treatment techniques
Harvesting	Passive sieving system that consists of a metallic mesh fitted on a wooden frame placed on a metallic tray
Sanitization and postprocessing	The harvested larvae are placed in sawdust for one night to make them empty their guts before being killed and dried in a gas oven at 50-60 °C for 6 hours
	Rearing
Egg production	Mating and oviposition occur in netted cages. Eggs laid by females on corrugated cardboard or banana leaves are harvested manually and incubated in small boxes containing wheat bran
Colony perpetuation	About 30% of young larvae are kept in the rearing unit in metallic trays filled with wheat bran for ten days. They are then transferred into concrete bays fitted with a self-harvesting system (30° slope that ends in a trench). Prepupae harvested from the trench are placed in plastic boxes fitted with fine mesh and containing sawdust to pupate

Note: Data were collected October - November 2017

6.4.3 Economic Viability and Impacts

Ento-Prise's facility is not yet financially viable as the products are not yet commercialized. A simple cost-benefit analysis of the system indicated that, based on the current productivity of the system, the revenue from the sales of the product is insufficient to cover the running costs.

One operator is needed to run a waste treatment capacity processing 0.3 tonnes of waste day^{-1}. However, if no operator is employed, i.e. if farmers themselves run the facility, they could make an annual profit of USD 1,920, with a four years' pay-back time on initial investment. But studies revealed that productivity should be further optimized to justify the adoption of the BSF technology by smallholder farmers. Obtaining the substrate at no charge would also significantly improve the economic performance of the facility.

A lifecycle assessment, conducted as part of the project, showed that the BSF process exhibits comparable or lower CO_2 emissions and GWP levels compared to landfilling or composting of fruit waste. Replacing conventional farming inputs with biofertilizer and dried larvae also showed fewer environmental impacts. For example, feeding guinea fowl with dried larvae-based meal instead of tuna-fish meal can reduce greenhouse gas (GHG) emissions by up to 25%.

Key success factors in this case are linked to a climate favorable to BSF rearing, the adoption of a low-tech and low-cost system adapted to the local context and the participation of both local research partners and international academic partners with experience in BSF rearing. Stakeholder analysis revealed high levels of acceptance for the use of both products (BSF larvae and biofertilizer) by smallholder farmers and consumers of end-products, and interest from various stakeholders to participate in BSF production supply chain.

6.5 Case Study 4: Enterra Feed

Enterra Feed is a private company founded in 2007. The first laboratory-scale system was built in Vancouver in 2009. Subsequently, Enterra Feed gradually upscaled its operation from the laboratory to the commercial scale through pilot and demonstration plots. In 2014, Enterra Feed moved its production to Langley near Vancouver to build a commercial-scale facility. Today, Enterra Feed continues to expand. It plans to increase the production capacity of its Langley facility from 100 to 1,000 tonnes of waste day^{-1} and to build new facilities in other Canadian cities, as well as in the USA and Europe.

6.5.1 Context

Vancouver is the largest city of British Columbia, located on the southwest coast of Canada. It is characterized by an oceanic climate and is one of the warmest Canadian cities in winter. According to the 2016 census, Vancouver has a population of about 630,000 and exhibits the highest population density in Canada. Greater Vancouver, which was home to about 2.5 million inhabitants in 2016, is also the third most populous metropolitan area in Canada, after Toronto and Montreal. Organic waste represented about 40% of the 392,630 tonnes of waste disposed of by households in 2014 in Metro Vancouver. Since 2015, the segregation of organic waste by households and businesses has become compulsory as part of Metro Vancouver's organics disposal ban.

6.5.2 Technology and Process

Production characteristics of the Enterra Feed facility are summarized in Table 29.

TABLE 29. THE ENTERRA FEED FACILITY: PRODUCTION CHARACTERISTICS.

	General
Waste input type	Preconsumer food waste (primarily fruit and vegetable waste, bread and grains)
Waste-processing capacity	100 tonnes daily
Products	Whole dried larvae, larvae meal, larvae oil and biofertilizer
Production capacity	7 tonnes daily of protein and oil feed ingredients and 8 tonnes daily of biofertilizer
Status of validation	Commercially proven
	Preprocessing
Preprocessing techniques	As some of the wastes received are still packaged, Enterra uses a depackaging machine. The waste is then shredded and mixed with small amounts of fish trim and waste grains to produce a suitable substrate to feed the BSF larvae
	Waste treatment
Configuration	Large trays stacked vertically. Enterra Feed's process is highly controlled and automated
Larval feeding period	14 days
	Harvesting and post-treatment techniques
Harvesting	Mechanical sieving
Sanitization and postprocessing	Larvae are screened, washed, cooked, dried, heat treated and packaged
	Rearing
Egg production	At full capacity, the process relies on a broodstock of 6 to 8 million adult flies. The hatchery consists of 50 mating cages of 54 m^3 each (2,700 m^3 in total) and produces 5 kg of eggs daily
Colony perpetuation	All the young larvae are used in the waste treatment unit but about 1% of the 100 million mature larvae harvested every day is sent back to the hatchery to pupate into flies

Note: Data were collected October - November 2017

6.5.3 Economic Viability and Impacts

In August 2018, Enterra announced its latest round of funding and plans to construct three new insect factories in Canada and the US. Enterra, which has raised about USD 10 million from funding in 2014, indicated that the funding puts the company's valuation over USD 100 million. Each new facility will cost around USD 30 million with the aim of increasing the company's production of black soldier fly 90 times. Investors include the Cibus Fund, the Wheatsheaf Group, Avrio Capital, and e.g. the poultry industry (PHW Gruppe).[1] Enterra Feed has received technical support from public institutions. It has also partnered with local research institutions and feed manufacturers for R&D.

In 2015, Vancouver banned the disposal of food and other organic waste, which promoted the emergence of solutions to divert organic waste from landfill. But Enterra can only process preconsumer food waste as feed ingredients. Indeed, use of postconsumer waste to produce larvae as feed in aquaculture and poultry production is prohibited.

The biofertilizer produced by Enterra Feed is approved for sale and listed as a permitted substance for organic farming in Canada, the USA and the EU. For feed products, federal approval was harder to obtain. Enterra had to wait until 2017 to get approval from both the Canadian Food Inspection Agency (CFIA) and the Food and Drug Administration (FDA) in the USA, for the use of its larvae-based feed products for poultry broilers, farmed salmon, arctic char and trout. The biofertilizer has been successfully tested by local and organic farmers and is now sold in Vancouver. Larvae-based feed ingredients have also proved to be suitable for feeding Atlantic salmon, tilapia, rainbow trout and poultry. Enterra's feed ingredients are being successfully sold on the US feed market. Enterra has secured at least 10 clients for its main feed products and currently sells all the biofertilizer produced to BioFert, a Canadian company manufacturing organic fertilizer products.

As of 2017, Enterra employed 32 full-time staff who are paid well over the minimum wage. Enterra activities divert 36,000 tonnes of waste annually from landfills. In addition, its process is expected to emit lower GHG emissions than composting and landfilling, as it does not produce any methane, relies on minimal machinery and produces feed ingredients that, on the local market, can replace conventional, carbon-intensive feed products. Moreover, no water is used to grow the larvae. Nevertheless, almost 20,000 m^3 of water could be recovered from the fruit and vegetable waste but this is not done in Canada as the demand and the climate do not make this recovery meaningful.

Key success factors in this case include the ability to secure abundant sources of waste and be paid to take care of it, institutional support, access to adequate funding, a conducive policy environment for supporting green businesses and making it compulsory to valorize organic waste and obtaining approval to sell its products on the North American market, characterized by a large demand for agricultural inputs.

6.6 Lessons Learned from the Case Studies

1. The BSF technology has been implemented in a wide range of contexts, i.e. in countries with different income levels, in different climates and at different scales. Indeed, the BSF technology is becoming more and more attractive, in both developed and developing countries, to entrepreneurs, who want to take advantage of a potentially huge market for animal feed.
2. The AgriProtein and Enterra Feed case studies have demonstrated that implementing the BSF technology on a large scale is technically feasible and economically viable, even in temperate climates, but requires large investments. Large-scale BSF facilities are characterized by high levels of automation and a highly controlled environment.
3. Medium-scale BSF facilities have the potential to improve organic waste management and create livelihood opportunities in low- and middle-income countries, but their economic viability has not yet been proven. The semicentralized organization suggested by Diener et al. (2015a) could improve the economic performance at this scale but such an organizational structure has not yet been tested. Medium-scale facilities, as they cannot afford to invest in the implementation of a highly controlled temperature environment to rear BSF, have so far mainly been operated in tropical climates.
4. Despite differences in operational design from one facility to another, the overall organization of the process is similar from one facility to another.
5. Preconsumer food waste seems to be so far the waste stream favored by BSF facilities, the exception being AgriProtein which is processing a wide range of organic materials. In this regard, large-scale facilities may be more able to treat mixed organic waste from multiple sources as they can invest in sorting and preprocessing equipment. On the other hand, treating a particular waste type from similar sources may be a better strategy for small- or medium-scale facilities, which cannot invest in expensive preprocessing machinery.
6. At all scales, securing continuously the right amount of waste is one of the biggest challenges faced by BSF facilities. In addition, the economics of waste sourcing influence the overall economic profitability of the facility, especially in small- and medium-scale

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[1] *Source:* https://agfundernews.com/enterra-feed-eyes-worlds-largest-insect-farm-in-wake-of-series-b-raise.html

BSF facilities. In this regard, regulation and policy regarding organic waste management influences the economics of waste sourcing. For example, in places where valorizing organic waste is compulsory, BSF facilities can get paid to take care of the waste. On the other hand, in the absence of regulation, BSF facilities may have to buy the waste from generators.

7. All the BSF facilities analyzed sell the same kind of products, i.e. BSF larvae-based feed ingredients and fertilizer. However, larger-scale facilities deliver higher grade products as they can invest in expensive refining equipment. To date, to the best of our knowledge, no commercial BSF facilities is postprocessing the lipid content of the larvae into biodiesel or extracting the chitin from BSF prepupae.
8. Facilities in developing countries seem to face fewer legal obstacles to sell the larvae-based feed products, while in high-income countries, this constitutes an important issue that may hinder the economic viability of the facility. However, as more and more companies are getting their products approved, this may become a less significant problem in the future.

7. STATE OF THE RESEARCH AND THE NEED FOR FURTHER STUDIES

7.1 Overview of the Literature Published on BSF Technology

To determine the status of the academic research on BSF technology, the focus of the studies reviewed, the main aspects they investigate, as well as the types of waste tested and the date of publication were analyzed. Regarding the focus of the studies reviewed, four categories were established, namely process engineering, implementation, sustainability aspects and products. The three first categories are based on the classification defined by Lohri et al. (2017). According to their definition, the *process engineering* category refers to the “articles of laboratory/ bench scale work with a technical focus on the basic fundamentals to understand and optimize the process”, while the *implementation* category includes studies dealing with “pilot/demonstration scale or case studies discussing the field application” and the *sustainability aspects* category regroups all the articles dealing with the economic, environmental or social aspects of the BSF technology. Finally, a fourth category, *products,* was added to the Lohri et al. (2017) classification to consider the articles which deal with the properties, application or safety of the products yielded by the BSF bioconversion process. The number of studies that fall into each category is shown in Figure 4 (some studies were classified into several categories).

Most of the studies focus on process engineering and the products of the process, while few studies deal with sustainability aspects, and even fewer with the (business) implementation of the BSF technology. In addition, studies published on the BSF technology have so far dealt extensively with the technical aspects of this treatment method, while the economic, environmental and social dimensions have been underexplored (see Figure 5). In addition, no article had the legal aspect of the BSF technology as its main topic.

Figure 6 shows that animal manure and food waste are the most extensively studied types of waste followed by vegetal agro-industrial waste and human feces as BSF feedstock.

FIGURE 4. MAIN FOCUS OF THE STUDIES REVIEWED (N=90).

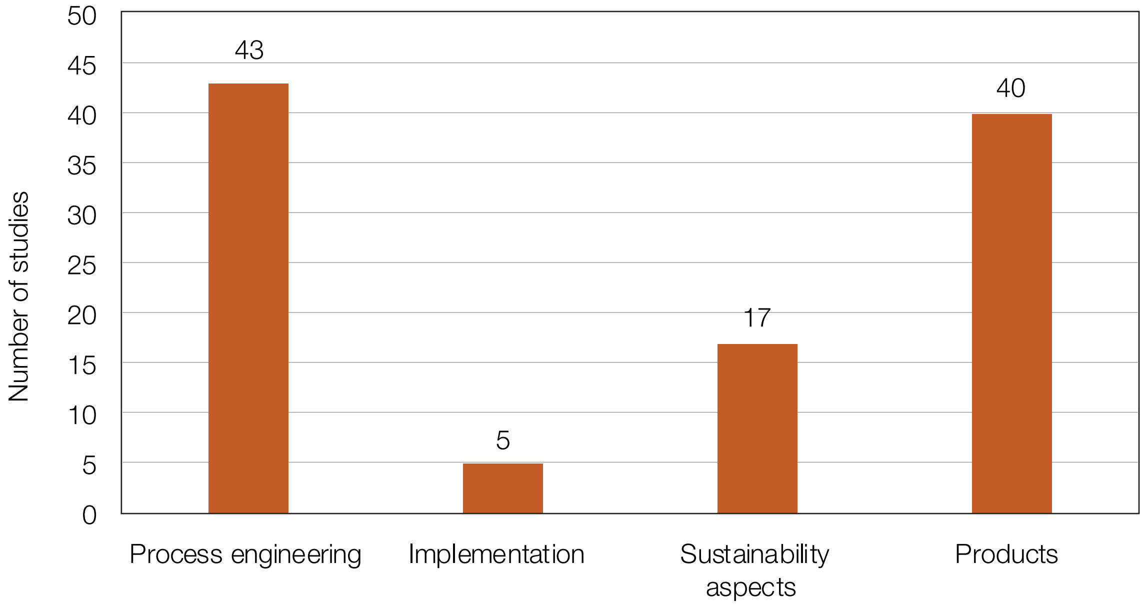


FIGURE 5. MAIN ASPECTS EXAMINED BY THE STUDIES REVIEWED (N=90).

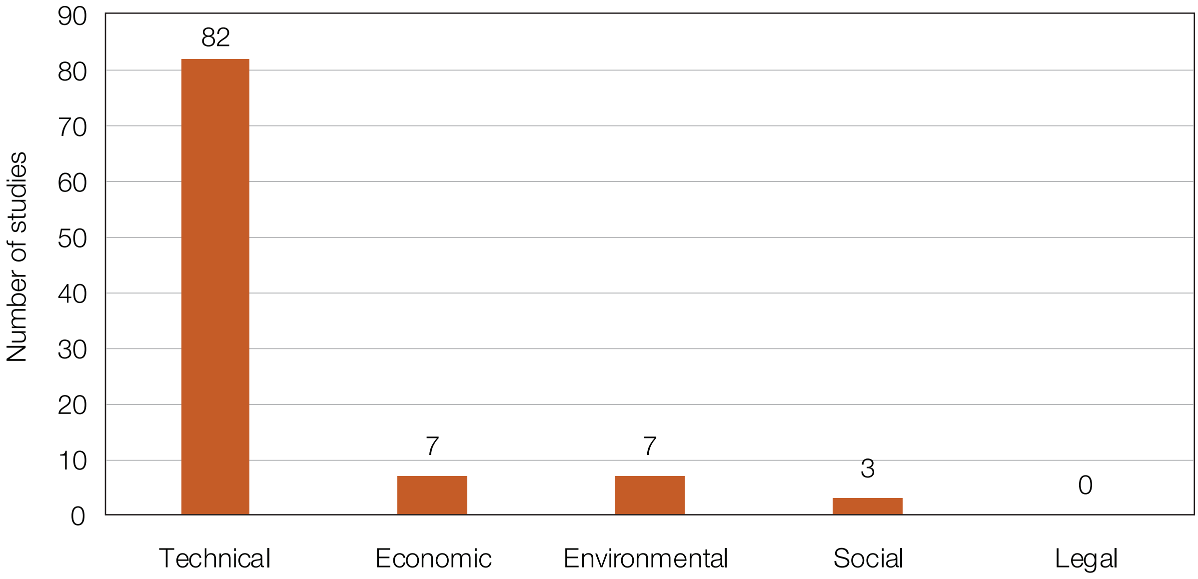
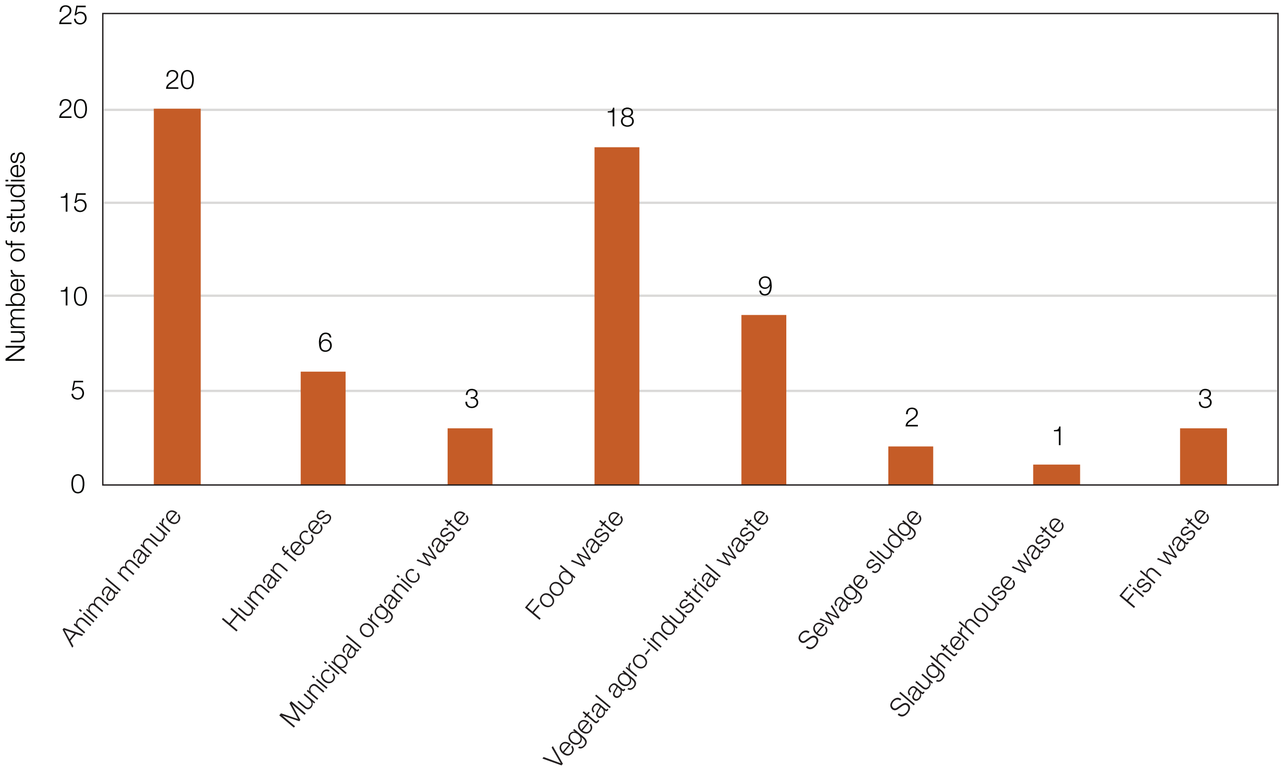


FIGURE 6. TYPES OF WASTE INVESTIGATED IN THE STUDIES REVIEWED (N=47).



Regarding the contexts and climates investigated, most studies (~80%) do not look at a specific context. For studies that focus on a particular context, slightly more studies deal with high-income countries (12%) than with low- and middle-income countries (9%). On the other hand, the same proportion (8%) of studies deals with temperate climates as with tropical climates (see Figure 7).

Finally, Figure 8 shows that research on the BSF technology is rather recent, as more than 75% of the studies reviewed were published after 2005, and more than 50% after 2010.

FIGURE 7. A) CONTEXTS, AND B) CLIMATE ZONES EXAMINED BY THE STUDIES REVIEWED (N=90).

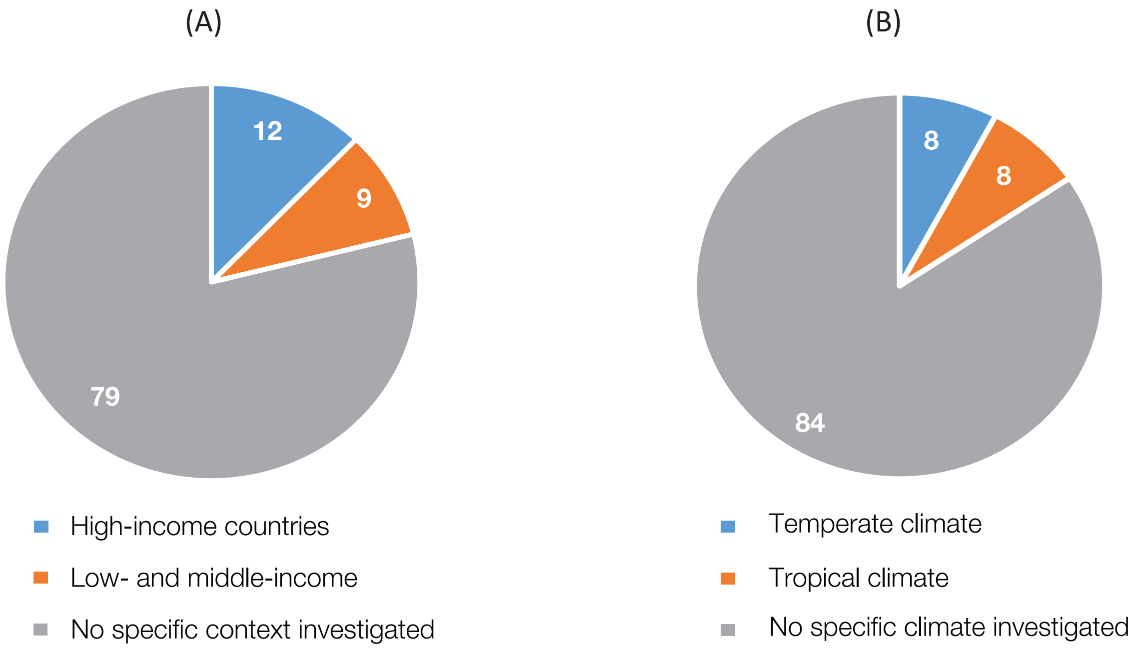
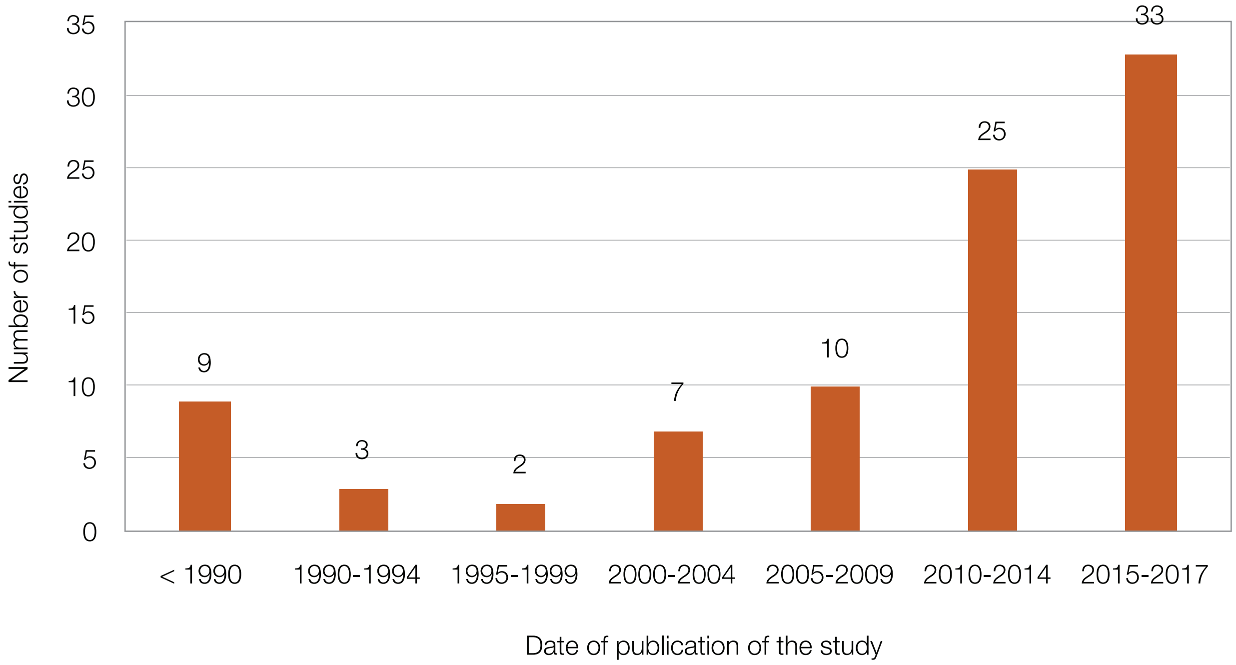


FIGURE 8. PUBLICATION DATES OF THE STUDIES REVIEWED (N=89).



7.2 Research Gaps

By reviewing the literature on organic waste treatment by the BSF, several research gaps and needs for further research were identified (Table 30).

Regarding the technical aspect of the BSF technology, several research gaps were identified pertaining to the feedstock, the breeding process, the waste treatment step and the products yielded by the process. Concerning the feedstock, the literature has established that BSF larvae can process a wide range of organic materials and mainly discusses the optimal moisture content of the waste input. However, little attention has been paid to how the physical-chemical composition of waste affects the BSF process. Optimal nutrient balance, pH and fiber content of the feedstock are also unknown. For the breeding of BSF, the optimal environmental conditions to artificially breed BSF have been extensively studied. However, the biological mechanisms underlying the mating of adult flies and oviposition by female BSF are not yet well understood. As such, optimizing this step is crucial as the consistent production of eggs is a key condition to ensuring an efficient BSF waste management system. In particular, the mechanisms involved in the choice of an oviposition site by female flies should be further investigated in order to design efficient oviposition media and attractant substrates to collect as many eggs as possible. Additionally, the optimal space and fly density for mating should be established.

Regarding the waste treatment step, the literature has focused mainly on establishing optimal larval density, feeding rate and regime, but the optimal thickness of the waste layer has been underexplored, although some authors have highlighted the importance of this factor in ensuring a well-functioning system (Perednia 2016; Dortmans et al. 2017; Yang 2017). To determine the range of suitable thicknesses for the waste layer, the oxygen requirement of the larvae should be understood. Another dimension that should be further investigated is the co-treatment of different waste types to optimize the performance of the system and enhance the value of the products. Co-digestion of different waste types has been tested by some authors like Rehman et al. (2017a, 2017b) and St-Hilaire et al. (2007b). However, only a limited combination of waste type has been investigated and the effect of mixing different waste types on both the performance of the system and the value of the products has not yet been fully documented.

In order to better understand the BSF technology, the nutrient flows through the process, as well as the role of microorganisms in the bioconversion process should be more extensively analyzed. As for the BSF process products, the optimal stage at which to harvest the larval biomass should be further discussed and trade-offs among nutritional value, digestibility and safety should be examined. The safety of both the larvae and the waste residue also need to be further explored. In particular, risks specific to each

TABLE 30. RESEARCH GAPS PERTAINING TO THE BSF TECHNOLOGY.

Theme	Research gaps
Feedstock	Optimal nutrient balance (e.g. C/N ratio), pH and fiber content.
Mating and oviposition	Mechanisms involved in the choice of an oviposition site by female flies, optimal space and fly density for mating.
Waste treatment	Optimal thickness for the waste layer, oxygen requirement of the larvae, co-digestion of different waste types, role of microorganisms in the bioconversion process, nutrient flows throughout the process.
Products	Optimal stage at which to harvest the biomass, safety of both products, properties of the waste residue, including nutrient composition, efficiency of the waste residue as a fertilizer, improvement of diet formulation of larvae meal, hygienization and refining methods for both products.
Implementation of the BSF technology	Optimal design and operating procedures for commercial BSF facilities, procedure for scaling up a BSF system.
Economic and business aspects	Start-up challenges, as well as profitability of running a medium-scale BSF facility, quantification of the revenues from the sales of the different products, comparison of the economic performance for different feedstocks, applications, and contexts (climate, income level, scale, etc.), and economic viability of differently sized enterprises.
Environmental aspects	Quantification of the CO_2 emissions associated with the BSF technology and comparison with other organic waste treatment methods, overall environmental performance of the BSF waste treatment process compared to other organic waste valorization options, taking into account all the environmental benefits associated with the replacement of other raw materials for animal feeding, fertilizer or biodiesel production, comparison of different applications for the BSF larvae in terms of environmental impacts (e.g. animal feed vs. biodiesel), comparison of the environmental performance of a BSF system for different substrates and specific inventory of GHG data for the BSF.
Social acceptance	Social acceptance of feeding animals with ingredients derived from BSF larvae reared on negatively perceived waste such as animal manure or human feces, willingness of waste operators or farmers to adopt this technology.

waste stream should be considered. In addition, the need to sanitize the different products and the performance of various sanitation techniques should be discussed. To date, the literature has mostly focused on the products derived from the larvae and the properties of the waste residue have been rarely discussed. Therefore, there is a need to analyze more extensively the properties of the waste residue, including its maturity, pH, nutrient and chemical composition, etc., and test its efficiency as a fertilizer. Finally, improvement of the diet formulation of larvae meal and refining methods for both products should be further discussed.

As discussed in the previous section, academic research focuses more on process engineering than on implementation of the BSF technology. As a result, most operating designs proposed in the literature have only been tested at the laboratory or bench scale. Except for a few practical guides or YouTube videos which give insights about the design and day-to-day activities of existing medium-scale pilot facilities (Caruso et al. 2013; Popoff and Maquart 2016a, 2016b; Dortmans et al. 2017), information regarding the design and operating procedures applied in the existing commercial BSF waste treatment facilities is not publicly available for competitive reasons (Lohri et al. 2017; Dortmans et al. 2017). Therefore, there is a need to bridge the knowledge gap between academic research and realistic day-to-day operation of a larger-scale BSF waste treatment facility. In addition, the procedure to scale up a BSF system should be discussed.

Regarding the economic dimension of the BSF technology, the financial requirements of starting and the profitability of running a medium-scale BSF facility have not yet been sufficiently covered, and should thus be further investigated. In this regard, implementing a semidecentralized fly-rearing facility to improve the economic viability of medium-scale BSF enterprises, as suggested by Diener et al. (2015a), could be explored. To improve economic analyses of BSF systems, there is a need to better quantify the revenues from the sales of the different process by-products. Finally, it would be interesting to compare the economic performance of BSF systems for different feedstocks, applications and contexts (climate, income level, scale, etc.).

As for the environmental aspect, the CO_2 emissions associated with the BSF technology should be quantified and compared to those of other organic waste treatment methods. In addition, to complement the work of Komakech et al. (2015), the overall environmental performance of the BSF waste treatment process, considering all the environmental benefits associated with the replacement of other raw materials for animal feeding, fertilizer or biodiesel production, should be compared to other organic waste valorization options. It would also be interesting to compare the different applications for the BSF larvae in terms of environmental impacts (e.g. animal feed vs biodiesel), as well as the environmental performance of a BSF system for different substrates to complete the work of Smetana et al. (2016). Finally, Salomone et al. (2017) pointed out the need to carry out specific GHG inventory data for the BSF.

Regarding the social aspect, to complement the consumer perception surveys carried out as part of the PROteINSECT project and by Popoff et al. (2017), the social acceptance of feeding animals with ingredients derived from BSF larvae reared on potentially negatively perceived waste such as animal manure or human feces, should be further analyzed, as well as the willingness of waste operators or farmers to adopt this technology.

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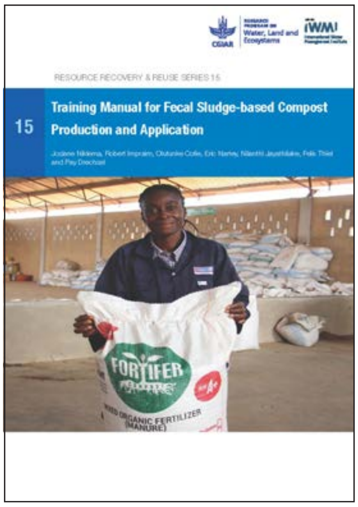

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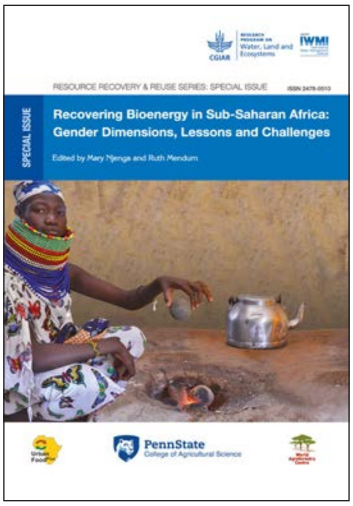

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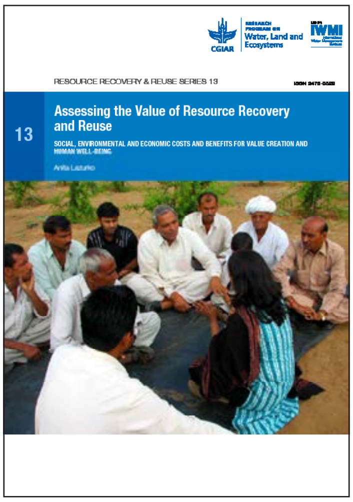

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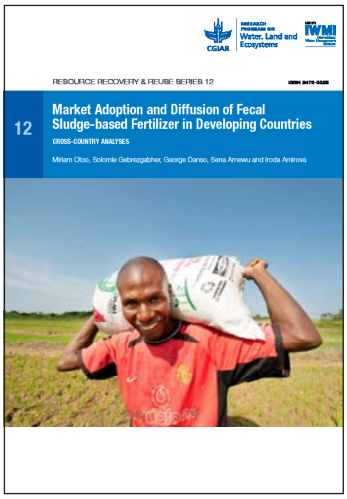

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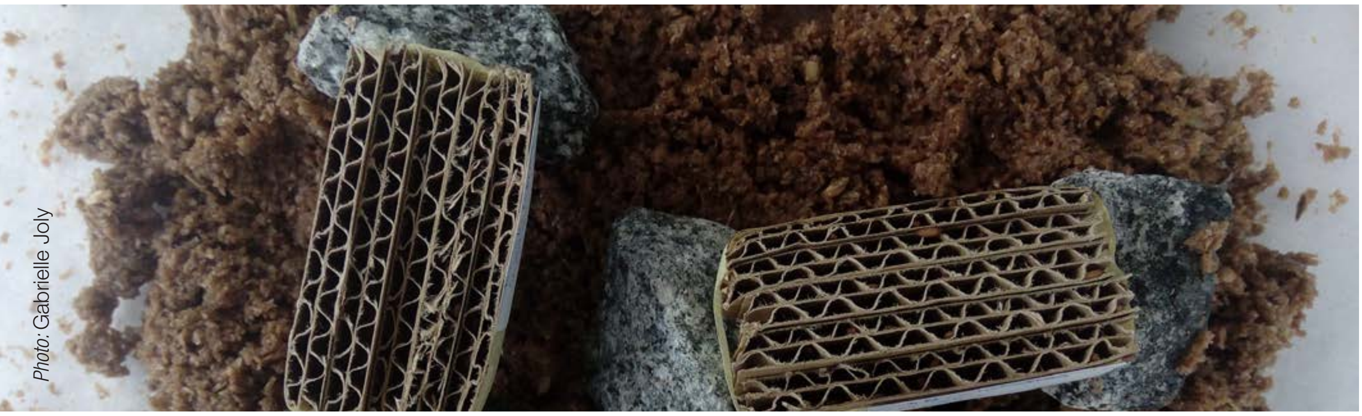
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