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# Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review

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**REVIEW ARTICLE**

## Abstract

The black soldier fly (BSF; *Hermetia illucens* L.; Diptera: Stratiomyidae) has been studied for its capability to convert organic waste to high quality protein, control certain harmful bacteria and insect pests, provide potential chemical precursors to produce biodiesel and for its use as feed for a variety of animals. Nutritional value of BSF larvae is discussed, as well as the effect of biotic and abiotic factors on both larval body composition and performance. Although BSF larvae contain high protein levels (from 37 to 63% dry matter; DM), and other macro- and micronutrients important for animal feed, the available studies on including BSF larvae in feed rations for poultry, pigs and fish suggest that it could only partially replace traditional feedstuff, because high or complete replacement resulted in reduced performance. This is due to factors such as high fat content (from 7 to 39% DM), ash (from 9 to 28% DM), and consequences of processing. Therefore, further studies are needed on nutrient composition, digestibility and availability for target species and on improved methods to process larvae, among other aspects. Additionally, it is clear that factors including quantity and quality of food, temperature, substrate moisture and/or larval crowding can affect BSF performance. However, the biology of BSF, in particular of the adult stage, has not been studied in detail. This review provides background information on the nutritional value of BSF larvae, its suitability as animal feed, biotic and abiotic conditions that affect its performance, and identifies which knowledge is required to ensure more dependable yields of BSF-mass rearing and development of economically feasible methods to take advantage of this species as animal feed.

**Keywords:** black soldier fly, *Hermetia illucens*, animal feed, nutritional value

## 1. Introduction

The demand for animal-derived protein sources will increase due to the combined effects of the growing human population and rising living standards in developing countries (FAO, 2009). Scarcity of resources has increased prices of animal feedstock during the last years, which represents 60-70% of production costs of animal production systems and results in competition between human food and animal feed. For instance, use of ingredients like fishmeal, fish oil, soybean meal and grains is on the rise in both human food and animal feed (Van Huis, 2013). Insects are proteinaceous (Bosch *et al.*, 2014) and have high feed conversion efficiencies and growth rates (Van Huis, 2013), making them a high quality and potentially profitable feedstuff for production animals (DeFoliart, 1989; Veldkamp *et al.*, 2012).

The animal production industry is faced with the challenge to develop innovative methods that are suited to meet future social, environmental and economic needs. Insects that can be sustainably reared on organic side streams could offer a suitable alternative animal protein source (Smetana *et al.*, 2016). There are various species of Coleoptera and Diptera that can be reared on low-grade bio-waste and convert it into high quality proteins. Examples are the beetles *Tenebrio molitor* Linnaeus, 1758 (Coleoptera: Tenebrionidae) (Li *et al.*, 2013) and *Rhynchophorus* spp.

Herbst, 1795 (Coleoptera: Curculionidae) (Cerda *et al.*, 2001; Elemo *et al.*, 2011), and the flies *Musca domestica* Linnaeus, 1758 (Diptera: Muscidae) (Awomyi, 2007; Calvert *et al.*, 1969) and *Hermetia illucens* Linnaeus, 1758 (Diptera: Stratiomyidae) (Newton *et al.*, 2005b).

The black soldier fly (BSF; *H. illucens*) is native to the Americas and is widespread from Argentina to central USA, throughout tropical and temperate regions (Sheppard *et al.*, 1994). Transported by humans, BSF has established in Australia, India, Africa and Europe (Gujarathi and Pejaver, 2013; Martínez-Sánchez *et al.*, 2011), because BSF can tolerate a broad range of environmental conditions (light, temperature, humidity).

For use as animal feed, BSF has several major advantages over other insect species. The species is polyphagous and its gut extracts have high amylase, lipase and protease activities (Kim *et al.*, 2011). Thus, it is employed in sustainable recycling of animal waste (Myers *et al.*, 2008; Nguyen *et al.*, 2013; Newton *et al.*, 2005b; Sheppard *et al.*, 1994), faeces (Diener *et al.*, 2009; Lalander *et al.*, 2013; Oonincx *et al.*, 2015a), and other types of organic waste (Diener *et al.*, 2011; Green and Popa, 2012; Gujarathi and Pejaver, 2013; Kalová and Borkovcová, 2013; Nguyen *et al.*, 2013; Rachmawati *et al.*, 2010), turning bio-waste into a high quality nutrient source for animal feed (Veldkamp *et al.*, 2012). As a result, BSF larvae have been used as feed for a variety of animals, including swine, poultry, and fish, and is being explored as an important ingredient for pet food.

Moreover, BSF is not a pest, so its rearing requires no specific precautionary measures and it reduces the presence of harmful bacteria (Erickson *et al.*, 2004; Liu *et al.*, 2008) in contrast to other dipteran species such as the house fly, *M. domestica*. The list of 'services' that have been developed includes the conversion of liquid manure and other domestic and agro-industrial waste types into a source of animal proteins (Caruso *et al.*, 2014). Because of the valuable nutrient content of the BSF larvae, they can be employed as the basis of a highly promising technology to sustain a circular economy, which is the concept of an economy that is producing no waste and reducing consumption of raw materials and energy by improving their utilisation, based on the interrelationships between the environment and economics. This concept will contribute to remediating the expected future scarcity of sufficient, nutritious and healthy food.

The present review aims to summarise the published information on the nutritional value of BSF larvae as animal feed. The review also discusses the biological aspects important to develop a BSF production system, as 'minilivestock' (Hardouin, 1995), and identifies knowledge gaps that require future research on this species.

## 2. Nutritional value of BSF larvae

### Body composition

Body composition of BSF larvae varies among substrates not only in protein content (ranging from 37 to 63% dry matter; DM) but also fat content, which has the most variation (ranging from 7 to 39% DM). Although BSF larvae on average contain both a high protein and fat content (St-Hilaire *et al.*, 2007a; Zheng *et al.*, 2012), body composition of the larvae depends on the quality and quantity of food ingested (Gobbi, 2012; Newton *et al.*, 2005a; Nguyen *et al.*, 2015). For instance, larvae fed swine manure have higher protein content than those fed cow manure (Newton *et al.*, 2005a; St-Hilaire *et al.*, 2007b), and diets based on spent grains result in higher protein content (Oonincx *et al.*, 2015b). The same applies for crude fat. Fat content accounted for about 30% of the BSF larval biomass fed on manures, but chicken manure supported maximal larval growth and crude fat content (Li *et al.*, 2011b) (Table 1). Nguyen *et al.* (2015) found that larvae fed fish and liver contained more protein and fat than those fed chicken feed. Large variation in body composition can also exist throughout the course of larval development itself. For example, crude protein content decreases with increasing age, the highest percentage was reported for larvae of 5 days old (61%), while it was less in 15 (44%) and 20 (42%) days old larvae (Rachmawati *et al.*, 2010).

Dry matter content of fresh larvae is between 20 and 44% (Diener *et al.*, 2009; Finke, 2013; Nguyen *et al.*, 2015; Oonincx *et al.*, 2015b; Sheppard *et al.*, 2008) and depends on both diet and larval stage (Rachmawati *et al.*, 2010), because DM is higher in the later instars.

### Amino acid content

Amino acid content of dried BSF larvae does not differ much between studies (Table 2), it appears that contents of some amino acids change in relation to larval diet, amino acid content showing a tendency to be slightly higher in larvae fed cattle manure (St-Hilaire *et al.*, 2007b; Newton *et al.*, 1977) than in larvae fed either swine manure (Newton *et al.*, 2005b) or chicken manure (Arango Gutiérrez, 2005). The amino acid profile shows that BSF larval protein is particularly rich in lysine (6-8% of protein content) (Sheppard *et al.*, 2008), and compares favourably with published values for animal feed (Newton *et al.*, 1977). For example, essential amino acid levels in larvae produced on swine manure are similar to soybean meal in lysine, leucine, phenylalanine, and threonine (Newton *et al.*, 2005b). When comparing BSF larvae and soy meal values (based on g/16 g N), larvae contain higher contents of alanine, methionine, histidine, and tryptophan, and a lower content of arginine than soybean meal.

**Table 1. Content of crude protein (CP) and crude fat (CF) of black soldier fly larvae reared on different substrates.**

| Substrate | %CP[1] | n | %CF[1] | n | References |
|---|---|---|---|---|---|
| Cattle manure | 42.1 | 1 | 34.8; 29.9 | 2 | Li *et al.*, 2011b; Newton *et al.*, 1977 |
| Chicken manure | 40.1±2.5 | 3 | 27.9±8.3 | 3 | Arango Gutiérrez *et al.*, 2004; Li *et al.*, 2011b; Sheppard *et al.*, 1994 |
| Swine manure | 43.6; 43.2 | 2 | 26.4±7.6 | 4 | Li *et al.*, 2011b; Manzano-Agugliaro *et al.*, 2012; Newton *et al.*, 2005b; St-Hilaire *et al.*, 2007b; |
| Palm kernel meal | 42.1; 45.8 | 2 | 27.5 | 1 | Rachmawati *et al.*, 2010 |
| Restaurant waste | – | | 39.2 | 1 | Zheng *et al.*, 2012 |
| Chicken feed | 47.9±7.1 | 3 | 14.6±4.4 | 3 | Bosch *et al.*, 2014; Nguyen *et al.*, 2015; Oonincx *et al.*, 2015b; |
| By-products[2] | 41.7±3.8 | 4 | – | | Oonincx *et al.*, 2015b |
| Liver | 62.7 | 1 | 25.1 | 1 | Nguyen *et al.*, 2015[3] |
| Fruits and vegetables | 38.5 | 1 | 6.63 | 1 | Nguyen *et al.*, 2015[3] |
| Fish | 57.9 | 1 | 34.6 | 1 | Nguyen *et al.*, 2015[3] |

[1] All values expressed on a dry matter basis. Values are mean ± standard deviation. n gives the number of replicates. If n=2, individual values are stated, separated by a semicolon.

[2] Beet molasses, potato steam peelings, spent grains and beer yeast, bread and cookie remains.

[3] Original values on a fresh matter basis have been converted to dry matter basis using the water content reported.

### Fatty acid content

BSF larvae and prepupae have been found to contain 58-72% saturated fatty acids and 19-40% mono- and poly-unsaturated fatty acids of total fat content (Kroeckel *et al.*, 2012; Li *et al.*, 2011c; Makkar *et al.*, 2014; Surendra *et al.*, 2016), containing high levels of lauric, palmitic and oleic acid (Surendra *et al.*, 2016). It seems that the fatty acid (FA) profile of larvae and prepupae depends on the FA composition of the diet (Table 3). For instance, BSF prepupae may incorporate some w-3 FA, like α-linolenic acid or eicosapentaenoic acid, when these occur in their diet (Sealey *et al.*, 2011; St-Hilaire *et al.*, 2007a). Oonincx *et al.* (2015b) found that higher dietary fat content resulted in a larger proportion of FA being metabolised to lauric acid, suggesting limited possibilities to adapt the FA profile of

**Table 2. Amino acid content (%DM and g/16 g nitrogen[1]) of black soldier fly (BSF) larvae fed swine, cattle or chicken manure and soy meal (data from Arango Gutiérrez, 2005; Makkar, *et al.* 2014; Newton *et al.*, 1977, 2005b; St-Hilaire *et al.*, 2007b).**

| Amino acid | Swine | Swine | Cattle | Chicken | BSF larvae[1] | Soy meal[1] |
|---|---|---|---|---|---|---|
| Alanine | 3.02 | 2.55 | 3.7 | 2.3 | 7.7 | 4.48 |
| Arginine | 2.65 | 1.77 | 2.2 | 2.12 | 5.6 | 7.48 |
| Aspartic acid | 3.72 | 3.04 | 4.6 | 1.36 | 11.0 | 12.1 |
| Cystine | – | 0.31 | 0.1 | 0.32 | 0.1 | 1.2 |
| Glycine | 2.28 | 2.07 | 2.9 | 2.31 | – | 4.25 |
| Glutamic acid | 3.78 | 3.99 | 3.8 | 2.75 | 10.9 | 19.3 |
| Histidine | 1.18 | 0.96 | 1.9 | 1.16 | 3.0 | 2.53 |
| Isoleucine | 2.03 | 1.51 | 2.0 | 1.55 | 5.1 | 5.04 |
| Leucine | 3.1 | 2.61 | 3.5 | 2.6 | 7.9 | 8.04 |
| Lysine | 2.62 | 2.21 | 3.4 | 2.14 | 6.6 | 6.39 |
| Methionine | 0.74 | 0.83 | 0.9 | 0.78 | 2.1 | 1.17 |
| Phenylalanine | 2.00 | 1.49 | 2.2 | 1.53 | 5.2 | 5.05 |
| Proline | 2.39 | 2.12 | 3.3 | 2.27 | 6.6 | 5.51 |
| Serine | 1.68 | 1.47 | 0.1 | 2.8 | 3.1 | 4.85 |
| Threonine | 1.78 | 1.41 | 0.6 | 1.87 | 3.7 | 3.93 |
| Tryptophan | – | 0.59 | 0.2 | 0.63 | 0.5 | – |
| Tyrosine | 3.08 | 2.38 | 2.5 | 2.62 | 6.9 | 3.64 |

**Table 3. Fatty acid content (% of total fatty acids) of black soldier fly larvae fed different substrates (data taken from Kroeckel *et al.*, 2012; Li *et al.*, 2011a; Oonincx *et al.*, 2015b; Sealey *et al.*, 2011; St-Hilaire *et al.*, 2007a; Zheng *et al.*, 2012).[1]**

| Fatty acid | Cattle manure (CM) n=3 | Chicken feed n=2 | CM + fish offal n=2 | By-products (high fat) n=2 | By-products (low fat) n=2 | Swine manure n=1 | Restaurant waste n=1 |
|---|---|---|---|---|---|---|---|
| Capric acid | 3.1 | 0.9 | – | 0.7; 0.8 | 0.3; 1.2 | – | 1.8 |
| Lauric acid | 26.7±7.8 | 47; 46.6 | 34.1; 37.1 | 28.9; 38.4 | 48.4; 50.7 | 49.3 | 23.4 |
| Myristic acid | 3.9±1.6 | 6.5; 9.2 | 6.3; 6.5 | 7.4; 7.8 | 9.9; 9.5 | 6.8 | – |
| Palmitic acid | 16.9±2.6 | 15; 12.7 | 14.3; 17.3 | 14.4; 17 | 11.6; 11.8 | 10.5 | 18.2 |
| Palmitoleic acid | 5.1±1.8 | 3.4 | 7.6 | 2.9; 3.4 | 4.7; 6.6 | 3.5 | 9.4 |
| Stearic acid | 5.3±1.5 | 2.2; 2.1 | 2; 2.4 | 2.4; 2.8 | 1.8; 2 | 2.8 | 5.1 |
| Oleic acid | 26.1±5.2 | 10.2-14 | 16.5; 18.8 | 15.9; 18.1 | 10.3; 10.8 | 11.8 | 27.1 |
| Linolenic acid | 4.5±2.4 | 9.4 | 3.9; 5.9 | 8.3; 17.1 | 3.6; 6 | 3.7 | 7.5 |
| α-linolenic acid | 0.2 | 0.6; 0.8 | 0.5; 0.7 | 0.8; 1.5 | 0.6; 1 | 0.1 | – |
| Stearidonic acid | – | – | 0.5 | – | – | – | – |
| Arachidonic acid | 0.04 | 0.1 | 0.2 | 0.1; 0.2 | 0.1; 0.6 | – | – |
| Eicosapenta-enoic acid | 0.07±0.1 | – | 1.8; 3.5 | – | – | – | – |
| Docosapenta-enoic acid | 0.01 | 0.1 | 0.1; 0.4 | – | – | – | – |
| Docosahexa-enoic acid | 0.06 | 0.1 | 0.4; 1.7 | – | – | – | – |

[1] Values are mean ± standard deviation. n gives the number of replicates. If n=2, individual values are stated, separated by a semicolon.

BSF larvae. Although diet has been suggested to exert strong influences on FA profiles, development and enzymology of fatty acid biosynthesis should also be taken into account to explain overall FA composition (Stanley-Samuelson *et al.*, 1988).

### Mineral content

BSF larvae contain higher mineral concentrations compared to other insects used in managed feeding programmes (Dierenfeld and King, 2009). Manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), phosphorus (P) and calcium (Ca) are found in high concentrations, with the highest Ca:P ratio reported being 8.4 (Makkar *et al.*, 2014). Sodium (Na) occurs in a lower concentration compared to the levels in other insects (Arango Gutiérrez, 2005; Dierenfeld and King, 2009). Newton *et al.* (2005b) found differences in mineral contents in BSF larvae reared on poultry or swine manure, possibly reflecting differences in mineral concentrations or availability between the two manure types (Table 4). For instance, P content was significantly higher in BSF reared on poultry manure. Ash content is relatively high and ranges between 9 and 28% DM (Finke, 2013; Makkar *et al.*, 2014). All authors report a high Ca content in BSF larvae, which might be partly explained by the fact that the epidermis of BSF secretes a deposit of calcium carbonate ($CaCO_3$) which may account for the high Ca and ash content (Johannsen, 1922) in Newton *et al.* (1977). Conversely, newly emerged adults contain very little Ca (0.03%) since Ca occurs concentrated in the shed pupal cuticle (Finke, 2013).

## 3. Suitability as animal feed

The following section will give a brief overview of studies that investigated BSF as animal feed.

### BSF as pig feed

BSF larval meal is a suitable ingredient in pig diets, because of its high contents of amino acids and calcium, and its good palatability. However, its relative deficiency in methionine and cystine requires the inclusion of those amino acids in balanced diets (Makkar *et al.*, 2014). Moreover, due to the high ash and crude fat content, BSF larvae should better be mixed with other proteinaceous ingredients (Newton *et al.*, 1977). Apparent digestibilities of dry matter and nitrogen tended to be better for the pigs fed soybean meal than BSF larval meal (85.3 and 77.2 vs 77.5 and 76%, respectively). In addition, weaned pigs did not perform well when fed on BSF larval meal, suggesting that additional refinement (cuticle removal and rendering) may be necessary to improve the performance of early weaned pigs (Newton *et al.*, 2005b).

### BSF as poultry feed

To the best of our knowledge there are few studies available on this topic. BSF larvae and prepupae, grown on swine manure or kitchen waste, have been used satisfactorily as a feed additive for young chicks (Hale, 1973). Partial replacement of soymeal (10-20%) for broilers showed a production performance, feed efficiency, mortality and

**Table 4. Mineral content (%DM) of black soldier fly larvae fed different substrates (data taken from Arango Gutiérrez, 2005; Dierenfeld and King, 2009; Finke, 2013; Newton *et al.*, 2005b).**

| Mineral | Poultry manure[1] | Swine manure | Chicken feed | Unknown |
|---|---|---|---|---|
| Calcium | 5; 7.8 | 5.36 | 3.14 | 2.41 |
| Phosphorus | 0.7; 1.5 | 0.88 | 1.28 | 0.91 |
| Magnesium | 0.37; 0.39 | 0.44 | 0.79 | 0.45 |
| Sodium | 0.15 | 0.13 | 0.27 | 0.23 |
| Potassium | 0.6; 0.7 | 1.16 | 1.96 | 1.17 |
| Iron | 0.01; 0.14 | 0.08 | 0.04 | 0.02 |
| Zinc | 0.01; 0.013 | 0.03 | 0.02 | 0.01 |
| Copper | 0.001 | 0.003 | 0.002 | 0.001 |
| Manganese | 0.02; 0.06 | 0.03 | 0.04 | 0.02 |

[1] If n=2, individual values are stated, separated by a semicolon.

carcass traits similar to those fed on commercial diets (Arango Gutiérrez, 2005; Cullere *et al.*, 2016; Zhang *et al.*, 2014b). The partial (50%) or full replacement of soybean cake by partly defatted BSF larval meal in a diet for layers did not affect their laying performance, nor feed efficiency, if compared to organic standard diets for layers (Maurer *et al.*, 2016).

The high apparent metabolisable energy and the amino acid apparent ileal digestibility coefficients of BSF larval meal, also make it a valuable ingredient for use in the formulation of broiler feeds (De Marco *et al.*, 2015). Additionally, Arango Gutiérrez (2005) suggested BSF larvae have a suitable mineral content for the nutrition of poultry, according to broiler mineral requirements, cited by the National Research Council (NRC, 1994).

### BSF as fish feed

Protein replacement in fish diets has been investigated using the meals obtained from both larvae and prepupae of BSF for the following fish species: Channel catfish (*Ictalurus punctatus*) (Bondari and Sheppard, 1981, 1987; Zhang *et al.*, 2014a,b), blue tilapia (*Oreochromis aureus*) (Bondari and Sheppard, 1981, 1987), hybrid tilapia (Nile tilapia, *Oreochromis niloticus* crossed with Sabaki tilapia, *Oreochromis spilurus*) (Furrer, 2011), rainbow trout (*Oncorhynchus mykiss*) (Sealey *et al.*, 2011; St-Hilaire *et al.*, 2007b), Atlantic salmon (*Salmo salar*) (Lock *et al.*, 2015), turbot (*Psetta maxima*) (Kroeckel *et al.*, 2012), and yellow catfish *(Tachysurus fulvidraco)* (Zhang *et al.*, 2014a).

Most of these studies showed that only low inclusion levels of BSF larvae have shown a similar performance to that of fish fed traditional feedstuff, which may be explained by high larval protein content (Bondari and Sheppard, 1987; Furrer, 2011; Newton *et al.*, 2005b; Sealey *et al.*, 2011; St-Hilaire *et al.*, 2007a; Zhang *et al.*, 2014a). High inclusion levels in fish feed (>33%) reduced not only fish growth (Kroeckel *et al.*, 2012; Newton *et al.*, 2005b; St-Hilaire *et al.*, 2007b), but also palatability of the diet and protein digestibility (Kroeckel *et al.*, 2012). The type of substrate on which BSF larvae were reared and the processing method might affect their utilisation by fish. For instance, BSF was included at least up to 50% in Atlantic salmon diet without affecting growth or fillet quality (Lock *et al.*, 2015).

Although the replacement of fish meal with insect meal can increase the amount of fat or change the nature of lipids in fish (St-Hilaire *et al.*, 2007b) and could, therefore, change the taste of the fish fillets, a partial inclusion of insect meal (10-50%) in the diet of fish does not affect FA profiles, aroma or flavour to the extent that this is perceived by consumers (Makkar *et al.*, 2014). For instance, no difference in organoleptic properties was found in Atlantic salmon (Lock *et al.*, 2015) or rainbow trout (Sealey *et al.*, 2011) fed up to 50% of BSF meal.

### BSF as feed for other animal species

Whole BSF larvae and pupae have been used to feed animals like alligators (*Alligator mississippiensis*) (Bodri and Cole, 2007) and mountain chicken frogs (*Leptodactylus fallax*) (Dierenfeld and King, 2009). A complete replacement of commercial feeds by BSF larvae fed to young alligators resulted in lower consumption and growth compared to commercial feeds. BSF larvae fed to Mountain chicken frogs resulted in poor nutrient digestibility. It seems that an unprocessed form of BSF may be less useful for species that swallow their food whole like these species. For example, calcium digestibility of whole BSF larvae in frogs was only 44% compared to 88% for BSF larvae that had been 'mashed' (Dierenfeld and King, 2009). Conversely, BSF larvae have been successfully utilized in captive feeding and breeding programmes for a number of lizard and amphibian species, mainly as source of minerals (Dierenfeld and King, 2009). Frass of BSF reared on dried distillers grains was evaluated as feed for commercial giant river prawn (*Macrobrachium rosenbergii*), resulting in similar performance as regular prawn feed, with better economic returns (Tiu, 2012).

## 4. BSF as minilivestock

Traditionally, the mass-rearing of insects has been focused on the production of beneficial insects, used as biological control agents for crop protection (Van Lenteren, 2003). In particular, most of the currently developed insect production businesses focus on predators and parasitoids for biological control (Manzano-Agugliaro *et al.*, 2012). Small non-domesticated animals, such as BSF and other insect species that have a potential benefit either nutritionally for food and/or economically for animal feed or other revenues, and are currently not being utilised to their full potential, could be bred under controlled conditions in captivity as in a traditional animal production system and have been called 'minilivestock' (Hardouin, 1995).

The development of BSF is influenced by abiotic factors (Furman *et al.*, 1959). In temperate countries reproduction of BSF requires temperature-controlled conditions (Alvarez, 2012). Therefore, technical improvements are necessary to arrive at economically viable BSF production systems (Alvarez, 2012). The use of BSF in low and middle income countries, where temperatures and sunlight are well suited for the propagation of the species year-round, offers small entrepreneurs the possibility of income generation without high investment costs. For instance, under field conditions in tropical countries, BSF was able to reduce organic waste more efficiently (65-75%) than in laboratory conditions in temperate countries (40%) (Diener, 2010). Tomberlin *et al.* (2002) found that specimens of a wild population reared under laboratory conditions had reduced size, weight, longevity, and caloric content in comparison to specimens collected directly from the wild.

## 5. Rearing BSF

The BSF is not active in the winter months in temperate countries, and this requires that rearing needs to take place indoors under artificial conditions (Zhang *et al.*, 2010). Under laboratory conditions BSF larvae, which have six larval instars including prepupae, reach the prepupal stage in two weeks at 30 °C (Furman *et al.*, 1959). Prepupae leave the food substrate to pupate (Sheppard *et al.*, 1994). Adults emerge after 10-14 d at 27-30 °C (Sheppard *et al.*, 2002). Adult BSF do not require food to survive but their longevity is increased when provided with a source of water (Tomberlin *et al.*, 2002), and sugar (Nakamura *et al.*, 2016) or honey (Rachmawati *et al.*, 2010). Two-day-old adults mate and females oviposit two days after copulation (Tomberlin and Sheppard, 2002). Females tend to lay eggs in crevices near food sources, with eggs hatching after four days at 27 °C (Booth and Sheppard, 1984).

As previously mentioned, life history characteristics of BSF, such as survival rate and development time, are determined by a variety of factors such as temperature (May, 1961) (Holmes *et al.*, 2016), relative humidity (Holmes *et al.*, 2012), food availability (Diener *et al.*, 2009), and food composition (Gobbi *et al.*, 2013), among others. The wide geographic distribution of BSF demonstrates its tolerance for a wide range of abiotic conditions. However, it is clear that there are optimal values for these conditions to maximise BSF performance. Threshold values of abiotic factors for BSF development are shown in Table 5.

### Larval food quality

Larval food quality is the determinant for the fitness of phytophagous insects with a non-feeding adult stage (Moreau *et al.*, 2006), this applies also to the BSF which stores most of its nutrients during the larval stage. BSF larvae prefer to consume diets with high fat content to build up a fat body necessary to complete development (Nguyen *et al.*, 2015; Tomberlin *et al.*, 2002). This is the reason why food quality is one of the most important factors affecting

**Table 5. Abiotic factors for rearing black soldier fly (BSF).**

| Abiotic factor | Min. | Optimal | Max. | References |
|---|---|---|---|---|
| Temperature (°C) | 12 | 26-27 | 36 | Booth and Sheppard, 1984; Holmes, 2010; Holmes *et al.*, 2016; Sheppard *et al.*, 1994; Tomberlin *et al.*, 2009 |
| Relative humidity (%) | 25 | 60-70 | 99 | Gobbi, 2012; Holmes *et al.*, 2012; Tomberlin and Sheppard, 2002 |
| Substrate moisture (%) | 40 | 52-70 | 70 | Fatchurochim *et al.*, 1989; Furman *et al.*, 1959; Tomberlin *et al.*, 2002 |
| Light intensity[1] | 60 | 135-200 | - | Alvarez, 2012; Holmes, 2010; Tomberlin and Sheppard, 2002; Zhang *et al.*, 2010 |

[1] Light intensity is expressed in μmol/m$^2$/s and affects mating and egg fertilisation of BSF. However, it has been suggested that light spectral composition plays a more important role in fertilisation than light intensity. Light-emitting diodes producing wavelengths in the UV, blue and green ranges have proved to increase the proportion of fertilised eggs (Oonincx *et al.*, 2016).

BSF growth rate and positively correlates with survival rate and larval length (Gobbi *et al.*, 2013; Newton *et al.*, 2005b). Moreover, BSF larval weight gain is also affected because of their potential dependence on bacteria as food (Liu *et al.*, 2008), which has also been found for other dipterans (Spiller, 1964). For instance, Yu *et al.* (2011) observed that the bacterium *Bacillus subtilis*, which was isolated from the BSF larval gut, promotes the growth and development of conspecific larvae by fermenting their food. This is probably because *B. subtilis* has the ability to digest protein and provide organic phosphorus (GuoHui *et al.*, 2010). Zheng *et al.* (2013) classified 78 genera of bacterial species obtained from larval, prepupal, pupal, adult, and egg samples of BSF. Bacteroidetes (42.0%) and Proteobacteria (33.4%) were the most dominant phyla associated with BSF across all life stages. These results indicate the high diversity of bacterial species associated with BSF. However, food substrate might influence microbial flora composition (Jeon *et al.*, 2011).

There are some studies about the effects of artificial diets on BSF development and adult life-history traits (Diener *et al.*, 2009; Gobbi *et al.*, 2013; Tomberlin *et al.*, 2002), and others related to the effects of different types of organic waste or industrial by-products on BSF life-history traits (Diener *et al.*, 2009; Lardé, 1989, 1990; Li *et al.*, 2011a,c; Myers *et al.*, 2008; Newton *et al.*, 2005a,b; Nguyen *et al.*, 2013, 2015; Oonincx *et al.*, 2015a,b; Rachmawati *et al.*, 2010; Sealey *et al.*, 2011; Sheppard *et al.*, 1994; Tomberlin *et al.*, 2002). Unfortunately, it is difficult to derive conclusions on the effect of food quality, because there are other aspects that also affect larval performance (larval density, substrate humidity or relative humidity) which are not reported.

In Table 6 life-history traits and performance are shown for BSF fed diets of similar macronutrient content (crude protein ~17%, crude fat ~4%): chicken feed, Chemical Specialties Manufacturers' Association fly larval medium and Gainesville house fly diet (Tomberlin *et al.*, 2002), at similar larval feeding rations (0.82±0.005 g/larva) and abiotic conditions (temperature 27±2 °C, relative humidity 70±10% and food moisture 66±4%), and larval densities between 0.1 and 2.5 larvae/$cm^2$.

More food available per larva positively affects both development and larval weight in BSF (Banks *et al.*, 2014; Diener *et al.*, 2009; Liu *et al.*, 2008; Myers *et al.*, 2008; St-Hilaire *et al.*, 2007b), but negatively affects waste reduction efficiency (Diener *et al.*, 2009). For chicken feed, Diener *et al.* (2009) reported an extended larval development (42 days) and a lower prepupal weight (0.09 g) but higher

**Table 6. Life-history traits and performance (± standard deviation; SD) of black soldier fly fed either chicken feed or diets of similar crude protein and fat contents.**

| Life-history or performance trait[1] | n[2] | Mean±SD | References |
|---|---|---|---|
| Larval developmental time (days) | 13 | 24.6±6.2 | Diener *et al.*, 2011; Gobbi, 2012; Li, 2014; Nguyen *et al.*, 2013; Oonincx *et al.*, 2015b; Tomberlin and Sheppard, 2001 |
| Pupal developmental time (days) | 8 | 14.8±6.8 | Gobbi, 2012; Nguyen *et al.*, 2013; Tomberlin and Sheppard, 2001 |
| Total cycle (days) | 8 | 40.2±6.4 | Gobbi, 2012; Nguyen *et al.*, 2013; Tomberlin, 2001 |
| Larval survival rate (%) | 5 | 89.4±9.4 | Gobbi, 2012; Li, 2014; Oonincx *et al.*, 2015b; Tomberlin and Sheppard, 2001 |
| Pupal survival rate (%) | 1 | 91 | Gobbi, 2012 |
| Larval weight (g FM) | 6 | 0.158±0.02 | Li, 2014; Nguyen *et al.*, 2013; Oonincx *et al.*, 2015b; Tomberlin and Sheppard, 2001 |
| Larval weight (g DM) | 1 | 0.044 | Li, 2014 |
| Prepupal weight (g FM) | 5 | 0.105±0.005 | Tomberlin and Sheppard, 2001 |
| Prepupal weight (g DM) | 3 | 0.037±0.004 | Diener *et al.*, 2011 |
| Pupal weight (g FM) | 3 | 0.150±0.03 | Gobbi, 2012 |
| Adult weight (g FM) | 3 | 0.053±0.01 | Tomberlin and Sheppard, 2001 |
| Adult weight (g DM) | 1 | 0.021 | Tomberlin and Sheppard, 2001 |
| Adult length (mm) | 1 | 15.8 | Gobbi, 2012 |
| Adult longevity (days) | 3 | 9.4±0.2 | Tomberlin and Sheppard, 2001 |
| ECI DM (%) | 4 | 17.6±6.3 | Diener *et al.*, 2011; Li, 2014; Oonincx *et al.*, 2015b |
| ECD DM (%) | 3 | 32.1±4.3 | Diener *et al.*, 2011; Li, 2014 |
| FCR | 1 | 1.8 | Li, 2014 |
| Larval DM content (%) | 3 | 36±1.8 | Diener *et al.*, 2011; Oonincx *et al.*, 2015b |

[1] DM = dry matter; ECD = efficiency of conversion of digested food; ECI = efficiency of conversion of ingested food; FCR = feed conversion ratio, defined as feed intake /average daily gain; FM = fresh matter.

[2] Number of independent experiments.

efficiency of conversion of digested food (ECD) (38%) at a low feeding ration (0.5 g/larva over the total larval development until prepupa), and observed shorter larval development time (15-16 days) and heavier prepupae (0.12-0.16 g fresh matter; FM), but low ECD (24.4-25.8%) at high feeding rations (1.66-3.18 g/larva). However, since BSF metabolism was not measured independently, these unexpected results for ECD may be spurious (Van Loon, 1991). For chicken feed, an optimum feeding ration seems to lie between 0.8-1.2 g of food per larva.

Information on the quality of organic waste as feed for BSF larvae is scattered and many of the biotic and abiotic factors that were mentioned above have not been reported. Thus, we have tried to compare life-history traits and performance of BSF larvae fed different substrates. Hence, we organised the information per type of substrate: faeces, vegetable and meat waste (Table 7).

In order to assess statistical differences among the studies, we performed parametric and non-parametric tests on the variables that were sufficiently replicated. One way ANOVA test and t-test were applied if the assumptions of homogeneity of variance and normality were met, while the Kruskal Wallis test was utilised for the data that did not meet these assumptions. Post-hoc Tukey test was performed to determine significance of differences ($P<0.05$). IBM SPSS Statistics version 21.0 was used (IBM Corp., Armonk, NY, USA). Larval developmental time was similar among all the diets (Kruskal-Wallis, $P=0.119$). However, survival rate was significantly lower when fed meat waste (ANOVA, Tukey post-hoc test, $P<0.05$). BSF larval dry matter yield (faeces and vegetable waste) differs neither among substrates (Student's t-test, $P=0.249$) nor does fresh matter yield differ between substrates (chicken feed or similar diets, faeces and vegetable waste; ANOVA, $P=0.084$). Prepupal weight (FM) tended to be higher in larvae fed faeces and vegetable waste than in larvae fed chicken feed (Kruskal-Wallis, $P=0.053$). However, prepupal dry weight was higher on vegetable waste than on faeces and chicken feed (Kruskal-Wallis, Pairwise comparisons, $P<0.05$). Neither ECI (chicken, faeces, vegetables) (Kruskal-Wallis, $P=0.838$) nor FCR (chicken, faeces, vegetables) (Kruskal-Wallis, $P=0.097$) were different across substrates.

These results should be considered as an attempt to explore how BSF performance is affected by food quality. The literature data available do not allow to identify the best substrate for BSF larvae in terms of larval performance. Overall conclusions are hampered due to the fact that variables differ not only among substrates, but also because of different biotic and abiotic conditions, as mentioned

**Table 7. Life-history traits and performance of BSF fed organic waste.**

| | Diet[2] | | | | | |
|---|---|---|---|---|---|---|
| **Life-history or performance trait[1]** | **Faeces[3]** | **n** | **Vegetable waste[4]** | **n** | **Meat waste[5]** | **n** |
| Larval developmental time (days) | 27.5±3.8 | 13 | 34±13.5 | 17 | 32.5±8.2 | 6 |
| Pupal developmental time (days) | 17.8±3 | 5 | 22.9±1.2 | 3 | 16.5±7.5 | 6 |
| Larval survival rate (%) | 89±7.5 | 3 | 78.9±13.2 | 10 | 48.2±8.7 | 3 |
| Larval weight (g FM) | 0.17±0.03 | 5 | 0.13±0.03 | 13 | 0.158 | 1 |
| Larval weight (g DM) | 0.031±0.02 | 4 | 0.028±0.01 | 5 | – | – |
| Prepupal weight (g FM) | 0.193±0.08 | 11 | 0.179±0.03 | 4 | – | – |
| Prepupal weight (g DM) | 0.018; 0.04 | 2 | 0.071±0.01 | 6 | – | – |
| Pupal weight (g FM) | – | – | – | – | 0.115±0.01 | – |
| Adult weight (g FM) | 0.046±0.01 | 4 | – | – | – | – |
| Adult longevity (days) | 12.5±2.1 | 4 | – | – | – | – |
| ECI (DM) (%) | 13.1±1.3 | 4 | 17.2±4.3 | 9 | – | – |
| FCR (FM) | 7.6±5.4 | 8 | 8.3±6.2 | 8 | – | – |
| Larval DM content (%) | – | – | 36.3±2.5 | 6 | – | – |

[1] DM = dry matter; FM = fresh matter.

[2] Values represent mean ± standard deviation. n gives the number of replicates. If n=2, individual values are stated, separated by a semicolon.

[3] Swine, poultry, cow and human faeces (Banks *et al.*, 2014; Diener *et al.*, 2011; Li *et al.*, 2011b,c; Myers *et al.*, 2008; Newton *et al.*, 2005a; Nguyen *et al.*, 2013; Oonincx *et al.*, 2015a; Sheppard *et al.*, 1994; St-Hilaire *et al.*, 2007a).

[4] Kitchen, fruit and vegetables, market, municipal organic and catering wastes, by-products, decaying palm kernel meal, coffee pulp, spent grains and distilled grains (Diener, 2010; Kalová and Borkovcová, 2013; Larde, 1990; Li, 2014; Nguyen *et al.*, 2013; Oonincx *et al.*, 2015b; Rachmawati *et al.*, 2010).

[5] Swine meal, meat meal, pig liver, fish rendering, cow manure plus fish offal (Gobbi, 2012; Nguyen *et al.*, 2013; St-Hilaire *et al.*, 2007a).

above. It is possible that controlled biotic and abiotic factors under laboratory conditions could influence the performance more strongly than the nutritional content of the substrate. In any case, larvae fed on good quality diets might need lower feeding rations to achieve a good performance than larvae fed on low quality diets. Thus, it seems possible to use a low quantity of feeding ration for BSF fed high quality food, as was suggested by (Sheppard, 1983), and to get a higher efficiency through more of the feed being converted to body mass.

As previously seen for chicken feed, higher feeding rations (i.e. amounts of food per larva) also positively affected development and larval, pupal and adult weights in BSF reared on cow manure. Myers *et al.* (2008) obtained a shorter developmental time (25.8-26.2 days) and, higher larval (0.16-0.18 g FM), prepupal (0.12-0.14 g FM) and adult (0.05-0.06 g FM) weights at high feeding ration for the whole experiment (4.7-6 g/larva). Moreover, adult longevity was also positively affected by high feeding ration. On the other hand, BSF prepupal weight (FM) could be more influenced by frequency of adding food than by feeding ration, for instance Banks *et al.* (2014) found that prepupae fed human manure at different feeding rations (12 and 1.2 g/larva), but at a same frequency (fed a single amount of faeces during the experiment) both reached an average body mass of 0.32 g FM. In contrast, larvae with a high feeding ration (12 g/larva) fed twice per week were on average lighter (0.23 g FM).

Regarding the effects of different types of manure on BSF larvae, Tomberlin *et al.* (2002) found that the growth period to prepupae on cow manure (almost 2 months) was slower than what has been reported for poultry manure or swine manure (4-6 weeks). Nguyen *et al.* (2013) obtained the lowest values for both weight and length gain for larvae fed pig manure in comparison with other organic wastes. Tomberlin *et al.* (2002) found that BSF larvae fed fresh (5 d-old) hen manure grew at half the rate of larvae fed 18 h old manure. It seems that aging of manure influences BSF development. This is probably due to a higher protein content of fresh manure (Sheppard, 1983). Oonincx *et al.* (2015a) reported extended development periods for BSF fed chicken (144 days), pig (144 days) and cow (215 days) dried manure. These extended development times could be an effect of the drying of the manure prior to the feeding experiment resulting in reduced nutritional quality.

Simon *et al.* (2011) suggested that diets with a higher proportion of protein increase the development period and survival rate of some predatory fly species. This may be a result of extended larval development periods, which allowed greater time for storing nutrients. Conversely in BSF, Oonincx *et al.* (2015b), who used vegetable by-products, observed larvae fed a diet high in both protein and fat and larvae fed control diet (chicken feed), also high in protein, resulted in a shorter development time (21 days) than the low protein diets (37 days). Nguyen *et al.* (2013, 2015) also observed a higher weight gain and length on both high protein and fat diets. In addition, low fat and protein content caused larvae to have longer developmental times (±30 days). However, high fat contents in feed (20-36% DM crude fat) could be detrimental for both larval and adult survival (Nguyen *et al.,* 2013, 2015).

The biodegradability of manure has been shown to be highly dependent on its lignin content, which comes mainly from forage fibre in the animal diet. Because poultry and swine diets generally contain little forage, it would be expected that their faeces would be better degradable than that of ruminants (St-Hilaire *et al.*, 2007a). The lower nutritional value of cow manure may explain why the larvae fed mixed (cow manure and fish offal) diets had higher average larval weights (0.14-0.16 g FM) compared to prepupae fed cow manure only (0.1 g FM) (St-Hilaire *et al.*, 2007a).

### Substrate characteristics

On the other hand, there are also physical factors influencing insect performance. For example, if the layer of food substrate is too thick, such as meat meal, swine meat, fish or liver, this reduces larval food intake resulting in lower survival and longer development (Gobbi, 2012; Gobbi *et al.*, 2013; Nguyen *et al.*, 2013). Lardé (1989) observed that BSF larvae like to grow on a more homogeneous, more dense and drier substrate, and it has been established that 60-70% moisture in chicken feed is adequate for BSF larvae. However, due to the variable composition of organic waste, food moisture is difficult to control and needs to be evaluated not only under laboratory, but also under field conditions where evaporation rate tends to be variable. Kalová and Borkovcová (2013) found that BSF larvae fed organic waste with high moisture content (>90%), survived, but had lower performance.

### Larval crowding

Larval crowding could be a major factor affecting the rate of development like has been reported for other dipteran species (Baldal *et al.*, 2005; Jannat and Roitberg, 2013; Jirakanjanakit *et al.*, 2007). Unfortunately, in few studies on BSF larval density has been reported. However, taking into account the size of containers used in different studies (Diener *et al.*, 2009; Gobbi, 2012; Myers *et al.*, 2008; Nguyen *et al.*, 2013; Oonincx *et al.*, 2015b; Sheppard *et al.*, 2002; Tomberlin *et al.*, 2009;) and assuming that the substrate layer is around 1-2 cm thick, an average density of 1.4 larvae per $cm^2$ can be calculated (min. 0.1 and max. 3.33 larvae/$cm^2$). Sheppard *et al.* (2002) suggest a density of 2.5 larvae per $cm^2$ of surface area for BSF fed chicken feed, in order to obtain an adequate growth. Banks *et al.* (2014) recorded similar larval developmental time (28-30 days) in

BSF larvae fed human faeces at different densities (0.02, 0.2, and 0.31 larva/$cm^2$), but they reached the highest prepupal weight (0.32 g FM) and the lowest FCR (10.4) at the lowest density (expression of density per unit surface is a proxy for actual relevant density which should be expressed per unit of volume). Density is an important biotic factor for dipterans such as BSF, because larval aggregation is characteristic for the biology of these species (Rivers and Dahlem, 2013). Larval aggregation has consequences such as heat accumulation and coprophagy and, resulting in more exhaustive nutrient utilisation and should be studied more in depth.

Since biotic and abiotic factors can affect both BSF performance and its nutritional value, it would be useful to select BSF strains adapted to specific factors, for a particular target animal to be fed with BSF larval meal. Many of the factors that clearly impact the performance of larval stages remain poorly studied. For instance, moisture and texture of the food, larval density and feeding ration could in part explain differences among the studies on BSF fed diets of similar composition.

## 6. Perspectives on BSF as animal feed

Most feeding studies with diets containing BSF larvae and prepupae have been conducted on fish, pigs and poultry. The available studies that include BSF larvae in poultry, pig and fish diets suggest that it could partially replace traditional feedstuff in their diets, because high or complete replacement did not result in good growth performance. There are some factors that might be affecting the performance of animals fed on diets containing BSF larvae or prepupae. First, BSF not only contains a high protein content, but also contains more fat than necessary in the diet of most animals, which could affect the digestibility and/or the palatability of BSF larval meal, as it was showed by Kroeckel *et al.* (2012). Second, BSF larvae also contain high levels of ash and hence higher levels of inclusion in the diet, especially of monogastrics, can decrease feed intake and cause other adverse effects (Makkar *et al.*, 2014). Third, an unprocessed form of BSF may affect its digestibility and be less utilisable for species that swallow their food whole (Dierenfeld and King, 2009). Fourth, although many authors have stated that BSF larval meal contains high quality protein, it is important to evaluate the quality for specific animals fed BSF meal and to define what limiting amino acids are provided by BSF meal.

In order to enhance the percentage replacement of traditional feedstuff, without compromising both growth or health, different strategies could be adopted in order to enhance nutritive value, the palatability and/or digestibility of the BSF larval meal. For example, it might be advisable to defatten BSF larvae and use the proteins for animal feed and the lipids for other purposes e.g. biodiesel production(Li *et al.*, 2011a; Surendra *et al.*, 2016), or as a good alternative lipid source in practical diets for animal feed (Li *et al.*, 2016). Thus, BSF larvae can convert dairy manure into biodiesel (Li *et al.*, 2011c), and compared with oil crops, BSF has higher reproductive capacity and a shorter lifecycle. BSF production requires less land than growing oil crops and may thereby alleviate conflicts between human food use and industrial use of crops (Li *et al.*, 2011b,c). Additionally, processing of BSF larvae (e.g. drying, defattening, cuticle removal) appears to increase nutrient availability and/or acceptability of the larvae, and their high dry matter content makes them easier and less costly to dehydrate than other fresh byproducts (Sheppard *et al.*, 2008). In order to increase the crude protein content of the insect meal, defattening is a feasible option (Makkar *et al.*, 2014; Newton *et al.*, 2005a). Surendra *et al.* (2016) found that mechanical pressing and solvent extraction significantly decrease the crude fat content (3.4%). For some species like frogs, mashed, rendered or chopped BSF larvae might increase Ca and P digestibilities (Dierenfeld and King, 2009).

Although most essential amino acid levels in BSF larvae are high, even higher than in soymeal or the FAO reference protein (Makkar *et al.*, 2014), some amino acids are low, like methionine which is one of the major limiting amino acids for growing pigs and broilers. However, each animal species has particular requirements. For example, while total sulphur-containing amino acids are first limiting when insects are incorporated into diets fed to mammals, to uricotelic animals such as birds and reptiles or ammoneotelic animals such as fish, arginine may also be important (Finke, 2013). Regarding young cats and dogs, Bosch *et al.* (2014) found that the first limiting amino acid in BSF larvae was the combined requirement for methionine and cystine. Moreover, *in vitro* protein digestibility of BSF larvae is high, 82-90% (Arango Gutiérrez *et al.*, 2004; Bosch *et al.*, 2014). However, the digestibility of BSF pupae was lower (77.7%) (Bosch *et al.*, 2014), which is likely caused by a high chitin content. On the other hand, BSF could be used to provide macro and micro-nutrients other than protein. For instance, this species can be used as suitable alternative feed high in minerals, taking away the need for mineral supplementation for some wild animals in captivity (Dierenfeld and King, 2009).

Further work is necessary to evaluate the possible use of BSF as a feed supplement or as the main source of protein in commercial diets. Bacteria isolated from BSF larvae also can be used as probiotic for improving animal performance, as was found in fish (Ushakova *et al.*, 2016). Before incorporating BSF larvae into the diet of an animal species, it is necessary to evaluate the exact composition of the BSF larvae and to compare it with the requirements of the animal species of interest, species with high protein requirements being particularly suitable candidates. In addition, digestibility measurements (*in vitro*, *in vivo* and *in situ*) are also considered necessary to predict accurately the protein quality of foods for animal diets. Likewise, differences in nutrient composition, digestibility and availability among the BSF developmental stages have been found. Since prepupae are easy to collect, high in protein, and have lower chitin content than pupae, the best larval stage to use as animal feed might be the prepupa. In any case, BSF processing issues also require further studies as the chitin content may not be the only factor responsible for these issues, and may even not be involved at all (Makkar *et al.*, 2014).

As discussed above, nutrient composition in BSF varies according to the diet, life stage and rearing conditions; therefore, the use of low-nutrient organic wastes to feed BSF larvae are aspects that require more in-depth studies (Henry *et al.*, 2015). Although there are some studies on the effect of various rearing media on biological parameters of BSF, most of them did not evaluate how those affected its nutritional composition. Hence, it is indispensable to perform rigorous experimental work on the nutritional quality of different diets and their effect on both feed conversion efficiency and body nutrient composition.

Next to nutrient quality, also other aspects like product safety and processability are important for using BSF in future animal feed formulations. For example, defatting has been showed a good method to process BSF larvae, however, temperatures involved need to be evaluated as they can influence nutrient composition and the growth of animals fed on them (Lock *et al.*, 2015). Regarding to palatability, the problem with lipids may be related more to their oxidation at a high temperature than to the actual high dietary lipid content or the presence of anti-nutritional factors, flavonoids and terpenoids in the insect meals (Belluco *et al.*, 2013; Shantibala *et al.*, 2014).

It is important to underline that BSF is a member of the complex detritivore community competing for resources, and the interaction with microbes significantly influences BSF oviposition preference (Zheng *et al.*, 2013) and changes the composition of the substrate. Hence, BSF larvae have been shown to reduce not only waste dry mass but also its content of nutrients such as nitrogen and phosphorus (Myers *et al.*, 2008; Sheppard *et al.*, 2008), and modify the microflora of manure, potentially reducing counts of harmful bacteria (Erickson *et al.*, 2004; Liu *et al.*, 2008). For example, larval activity significantly reduced *Escherichia coli* 0157:H7 and *Salmonella enterica* serotype Enteritidis (ME 18) populations in poultry manure (Erickson *et al.*, 2004). Lalander *et al.* (2013) found a reduction in *Salmonella* spp. in human faeces after eight days of starting the experiment. Arango Gutiérrez *et al.* (2004) conducted a microbiological study on BSF prepupal meal and found *Salmonella* spp. and *E. coli* to be absent.

Temperature also significantly influenced the ability of BSF larvae to develop and reduce *E. coli* counts with greatest suppression occurring at 27 °C (Liu *et al.*, 2008). Zheng *et al.* (2013) mentioned that *Providencia* appears to be a candidate for vertical transmission in BSF as it was found in adults and eggs. The possibility of bacteria being retained through successive BSF life stages should be investigated and if shown could necessitate the testing of the initial bacterial load and diversity in these flies before introduction into waste or feed. In this way any inadvertent disease transmission can be mitigated and can eliminate those bacteria that pose potential harm to animals or humans. Additionally, BSF larvae seem to secrete chemicals that prevent other fly species to lay eggs on a food source colonised by BSF, which results in effective reductions of the common housefly, *M. domestica* (Bradley and Sheppard, 1984).

Regarding toxic feed contaminants, Diener (2010) found cadmium, lead and zinc in BSF prepupae fed on organic waste. None of the three heavy metals had significant effects on life cycle traits (prepupal weight, development time, sex ratio) nor on the bilateral symmetry of the adult flies. However, cadmium accumulated in the prepupae and could thereby potentially limit its use in the production of animal feed. Diener (2010) also concluded that neither lead nor zinc accumulate in larvae or prepupae, which means concerns about the use of prepupae in animal feed might be less critical. Potential hurdles, such as the bioaccumulation of insecticides, medical drugs, heavy metals and natural toxins can be controlled in mass rearing setups through quality control of their rearing substrates (Van der Spiegel *et al.*, 2013), especially when organic by-products are an important feed source for BSF.

In relation to its ecological footprint, the BSF has favourable properties, not only due to its ability to recycle nutrients, but also because insects have been reported to emit fewer greenhouse gases and less ammonia than cattle or pigs (Oonincx *et al.*, 2010). Moreover, they require significantly less land and water than cattle rearing (Van Huis *et al.*, 2013). Accurate data must still be generated on feed conversion efficiency of BSF and its use of water and substrate both per unit of biomass and nutrient production, to make decisions on the environmental impacts of using BSF meals rather than other conventional feed resources. Therefore, even though BSF larvae are not a major contender of other ingredients for animal feed yet, taking into account these economical and ecological aspects, BSF larvae might be included in the industrial formulation of animal feed. These perspectives will still require further research and adaptations, but are already supported by scientific results from several research projects or applications around the world.

## 7. Perspectives on BSF as minilivestock

If BSF meal is to become a significant part of the animal diets produced by the feed industry, it is necessary to ensure a steady production of BSF in terms of quantity, quality and price. Despite BSF having a favourable nutritional content, the actual cost of the production and harvesting of BSF is still high. There is a need for establishing cost-effective and optimised insect mass-rearing facilities that use well-defined substrates, producing insects of a defined quality (macro- and micronutrients). It is necessary to take advantage of the multiple benefits of using it in an animal production system and/or a mass-rearing production (minilivestock). Given that BSF larvae consume a wide range of organic resources, recycling nutrients not only adds to overall sustainability of its production, but the use of locally produced material to feed BSF larvae might contribute to the economic efficiency of the operations, reducing the costs of the feed. In addition, the use of BSF oil for biofuel production and use of the defatted meal as animal feed would enhance the economic returns from the mass-rearing establishments. An alliance between companies and both small and big agricultural producers should be reached in order to achieve economic profit for both sides.

The use of BSF minilivestock is a challenge because despite ample research on various topics related to the effect of biotic and abiotic factors on its larval biology not only in tropical regions, but also in temperate regions, little information is available on how these factors affect the mature stages of BSF, such as mating success, fecundity, egg size and fertility. The latter is particularly important because reproductive potential critically depends upon resource accumulation during the larval stage in BSF. Therefore, it is essential to study all fitness related life-history traits to fully understand the effects of larval food quality on fitness. This knowledge will allow to increase body mass and/or size of individuals to maximise the continuous production of eggs necessary for the mass-rearing of this species.

Filling all the knowledge gaps identified above will contribute to controlled management of BSF mass rearing. There is a need to improve risk assessment methodologies. Scientific understanding of BSF as minilivestock, embedded in local contexts, needs to be addressed to achieve that people not only in tropical and developing countries, but also in temperate regions could take advantage of this species through new approaches, based on sustainability, on protection of the environment, to meet increasing food demands. Indeed, this species holds promise to become an integral part of livestock and agriculture.

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## References


Alvarez, L., 2012. The role of black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae) in sustainable waste management in northern climates. PhD thesis, University of Windsor, Windsor, ON, Canada. Available at: http://scholar.uwindsor.ca/etd/402.

Arango Gutiérrez, G.P., 2005. Aportes nutricionales de la biomasa de *Hermetia illucens* L. (Diptera: Stratiomyidae) en la cría de pollos de engorde. MSc thesis, Universidad Nacional de Colombia, Bogotá, Colombia.

Arango Gutiérrez, G.P., Vergara Ruiz, R.A. and Mejía Vélez, H., 2004. Compositional, microbiological and protein digestibility analysis of the larva meal of *Hermetia illucens* L. (Diptera: Stratiomyidae) at Angelópolis-Antioquia, colombia. Revista Facultad Nacional de Agronomía, Medellín 57: 2491-2500.

Awomyi, T., 2007. Health, nutrional and consumers' acceptability assurance of maggotmeal inclusion in livestock diet: a review. International Journal of Tropical Medicine 2: 52-56.

Baldal, E., Van der Linde, K., Van Alphen, J., Brakefield, P. and Zwaan, B., 2005. The effects of larval density on adult life-history traits in three species of *Drosophila*. Mechanisms of Ageing and Development 126: 407-416.

Banks, I.J., Gibson, W.T. and Cameron, M.M., 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Tropical Medicine and International Health 19: 14-22.

Belluco, S., Losasso, C., Maggioletti, M., Alonzi, C.C., Paoletti, M.G. and Ricci, A., 2013. Edible insects in a food safety and nutritional perspective: a critical review. Comprehensive Reviews in Food Science and Food Safety 12: 296-313.

Bodri, M.S. and Cole, E.R., 2007. Black soldier fly (*Hermetia illucens* L.) as feed for the American alligator (*Alligator mississippiensis*). Georgia Journal of Science 65: 82-88.

Bondari, K. and Sheppard, D.C., 1981. Soldier fly larvae as feed in commercial fish production. Aquaculture 24: 103-109.

Bondari, K. and Sheppard, D.C., 1987. Soldier fly, *Hermetia illucens* L., larvae as feed for channel catfish, *Ictalurus punctatus* (Rafinesque), and blue tilapia, *Oreochromis aureus* (Steindachner). Aquaculture and Fisheries Management 18: 209-220.

Booth, D.C. and Sheppard, D.C., 1984. Oviposition of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae): eggs, masses, timing, and site characteristics. Environmental Entomology 13: 421-423.

Bosch, G., Zhang, S., Oonincx, D.G.A.B. and Hendriks, W.H., 2014. Protein quality of insects as potential ingredients for dog and cat foods. Journal of Nutritional Science 3(e29): 1-4.

Bradley, S.W. and Sheppard, D.C., 1984. House fly oviposition inhibition by larvae of *Hermetia illucens*, the black soldier fly. Journal of Chemical Ecology 10: 853-859.

Calvert, C.C., Martin, R.D. and Morgan, N.O., 1969. House fly pupae as food for poultry. Journal of Economic Entomology 62: 938-939.

Caruso, D., Devic, E., Subamia, I., Talamond, P. and Baras, E., 2014. Technical handbook of domestication and production of Diptera black soldier fly (BSF), *Hermetia illucens*, Stratiomyidae. IRD, Jakarta, Indonesia, 141 pp. Available at: http://tinyurl.com/n7t8bt4.

Cerda, H., Martinez, R., Briceno, N., Pizzoferrato, L., Manzi, P., Ponzetta, M.T., Marin, O. and Paoletti, M., 2001. Palm worm (*Rhynchophorus palmarum*) traditional food in Amazonas, Venezuela – Nutritional composition, small scale production and tourist palatability. Ecology of Food and Nutrition 40: 13-32.

Cullere, M., Tasoniero, G., Giaccone, V., Miotti-Scapin, R., Claeys, E., De Smet, S. and Dalle Zotte, A., 2016. Black soldier fly as dietary protein source for broiler quails: apparent digestibility, excreta microbial load, feed choice, performance, carcass and meat traits. Animal 10: 1923-1930.

De Marco, M., Martínez, S., Hernandez, F., Madrid, J., Gai, F., Rotolo, L., Belforti, M., Bergero, D., Katz, H. and Dabbou, S., 2015. Nutritional value of two insect larval meals (*Tenebrio molitor* and *Hermetia illucens*) for broiler chickens: apparent nutrient digestibility, apparent ileal amino acid digestibility and apparent metabolizable energy. Animal Feed Science and Technology 209: 211-218.

DeFoliart, G.R., 1989. The human use of insects as food and as animal feed. Bulletin of the Entomological Society of America 35: 22-35.

Diener, S., 2010. Valorisation of organic solid waste using the black soldier fly, *Hermetia illucens.* Low and middle-income countries. PhD thesis, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Dübendorf, Switzerland.

Diener, S., Zurbrügg, C. and Tockner, K., 2009. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. Waste Management and Research 27: 603-610.

Diener, S., Zurbrügg, C., Gutiérrez, F.R., Nguyen, D.H., Morel, A., Koottatep, T. and Tockner, K., 2011. Black soldier fly larvae for organic waste treatment – prospects and constraints. In: Proceedings of the WasteSafe – 2nd International Conference on Solid Waste Management in the Developing Countries, Khulna, Bangladesh.

Dierenfeld, E.S. and King, J., 2009. Digestibility and mineral availability of phoenix worms (*Hermetia illucens*) ingested by mountain chicken frogs (*Leptodactylus fallax*). Journal of Herpetological Medicine and Surgery 18: 100-105.

Elemo, B.O., Elemo, G.N., Makinde, M. and Erukainure, O.L., 2011. Chemical evaluation of african palm weevil, *Rhychophorus phoenicis*, larvae as a food source. Journal of Insect Science 11: 146.

Erickson, M.C., Islam, M., Sheppard, C., Liao, J. and Doyle, M.P., 2004. Reduction of *Escherichia coli* O157:H7 and *Salmonella enterica* serovar enteritidis in chicken manure by larvae of the black soldier fly. Journal of Food Protection 67: 685-690.

Fatchurochim, S., Geden, C. and Axtell, R., 1989. Filth fly (Diptera) oviposition and larval development in poultry manure of various moisture levels. Journal of Entomological Science 24: 224-231.

Finke, M.D., 2013. Complete nutrient content of four species of feeder insects. Zoo Biology 32: 27-36.

Food and Agriculture Organisation (FAO), 2009. How to feed the world in 2050. High-level expert forum on 'How to feed the world in 2050'. FAO, Rome, Italy. Available at: http://tinyurl.com/lzypw4a.

Furman, D.P., Young, R.D. and Catts, P.E., 1959. *Hermetia illucens* (Linnaeus) as a factor in the natural control of *Musca domestica* L. Journal of Economic Entomology 52: 917-921.

Furrer, T., 2011. Finding an adequate tilapia feed for rural fish farmers in Mombasa. BSc thesis, Zurich University of Applied Sciences, Winterthur, Switzerland. Available at: http://tinyurl.com/mblptmd.

Gobbi, F.P., 2012. Biología reproductiva y caracterización morfológica de los estadios larvarios de *Hermetia illucens* (L., 1758) (Diptera: Stratiomyidae). Bases para su producción masiva en Europa. PhD thesis, Universidad de Alicante, Alicante, Spain.

Gobbi, P., Martínez-Sánchez, A. and Rojo, S., 2013. The effects of larval diet on adult life-history traits of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). European Journal of Entomology 110: 461.

Green, T.R. and Popa, R., 2012. Enhanced ammonia content in compost leachate processed by black soldier fly larvae. Applied Biochemistry and Biotechnology 166: 1381-1387.

Gujarathi, G. and Pejaver, M., 2013. Occurrence of black soldier fly *Hermetia illucens* (Diptera: Stratiomyidae) in biocompost. Research Journal of Recent Sciences 2: 65-66.

GuoHui, Y., ChunYan, N., GuoBao, H., Lin, Z., Qiang, X. and Ping, C., 2010. Isolation and identification of bacteria producing enzymes from gut and skin of black soldier fly (*Hermetia illucens*) larvae. Chinese Bulletin of Entomology 47: 889-894.

Hale, O.M., 1973. Dried *Hermetia illucens* larvae (Diptera: Stratiomyidae) as a feed additive for poultry. Journal of the Georgia Entomological Society 8: 16-20.

Hardouin, J., 1995. Minilivestock – from gathering to controlled production. Biodiversity and Conservation 4: 220-232.

Henry, M., Gasco, L., Piccolo, G. and Fountoulaki, E., 2015. Review on the use of insects in the diet of farmed fish: past and future. Animal Feed Science and Technology 203: 1-22.

Holmes, L., VanLaerhoven, S. and Tomberlin, J., 2016. Lower temperature threshold of black soldier fly (Diptera: Stratiomyidae) development. Journal of Insects as Food and Feed 2: 1-8.

Holmes, L.A., 2010. Role of abiotic factors on the development and life history of the black soldier fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae). PhD thesis, University of Windsor, Windsor, ON, Canada. Available at: http://tinyurl.com/n6cc2cc.

Holmes, L.A., Vanlaerhoven, S.L. and Tomberlin, J.K., 2012. Relative humidity effects on the life history of *Hermetia illucens* (Diptera: Stratiomyidae). Environmental Entomology 41: 971-978.

Jannat, K.N.E. and Roitberg, B.D., 2013. Effects of larval density and feeding rates on larval life history traits in *Anopheles gambiae* (Diptera: Culicidae). Journal of Vector Ecology 38: 120-126.

Jeon, H., Park, S., Choi, J., Jeong, G., Lee, S.B., Choi, Y. and Lee, S.J., 2011. The intestinal bacterial community in the food waste-reducing larvae of *Hermetia illucens*. Current Microbiology 62: 1390-1399.

Jirakanjanakit, N., Leemingsawat, S., Thongrungkiat, S., Apiwathnasorn, C., Singhaniyom, S., Bellec, C. and Dujardin, J.P., 2007. Influence of larval density or food variation on the geometry of the wing of *Aedes* (*Stegomyia*) *aegypti*. Tropical Medicine and International Health 12: 1354-1360.

Kalová, M. and Borkovcová, M., 2013. Voracious larvae *Hermetia illucens* and treatment of selected types of biodegradable waste. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 61: 77-83.

Kim, W., Bae, S., Kim, A., Park, K., Lee, S., Choi, Y., Han, S., Park, Y. and Koh, Y., 2011. Characterization of the molecular features and expression patterns of two serine proteases in *Hermetia illucens* (Diptera: Stratiomyidae) larvae. BMB Reports 44: 387.

Kroeckel, S., Harjes, A.G.E., Roth, I., Katz, H., Wuertz, S., Susenbeth, A. and Schulz, C., 2012. When a turbot catches a fly: evaluation of a pre-pupae meal of the black soldier fly (*Hermetia illucens*) as fish meal substitute – Growth performance and chitin degradation in juvenile turbot (*Psetta maxima*). Aquaculture and Fisheries Management 364-365: 345-352.

Lalander, C., Diener, S., Magri, M.E., Zurbrügg, C., Lindström, A. and Vinnerås, B., 2013. Faecal sludge management with the larvae of the black soldier fly (*Hermetia illucens*) from a hygiene aspect. Science of the Total Environment 458: 312-318.

Lardé, G., 1989. Investigation on some factors affecting larval growth in a coffee-pulp bed. Biological Wastes 30: 11-19.

Larde, G., 1990. Recycling of coffee pulp by *Hermetia illucens* (Diptera, Stratiomyidae) larvae. Biological Wastes 33: 307-310.

Li, C.-J., 2014. Conversion of spent grains and DDGS by black soldier flies. MSc thesis, Laboratory of Entomology, Wageningen University, Wageningen, the Netherlands.

Li, L., Zhao, Z. and Liu, H., 2013. Feasibility of feeding yellow mealworm (*Tenebrio molitor* L.) in bioregenerative life support systems as a source of animal protein for humans. Acta Astronautica 92: 103-109.

Li, Q., Zheng, L., Cai, H., Garza, E., Yu, Z. and Zhou, S., 2011a. From organic waste to biodiesel: black soldier fly, *Hermetia illucens*, makes it feasible. Fuel 90: 1545-1548.

Li, Q., Zheng, L., Hou, Y., Yang, S. and Yu, Z., 2011b. Insect fat, a promising resource for biodiesel. Journal of Petroleum and Environmental Biotechnology S2: 001.

Li, Q., Zheng, L., Qiu, N., Cai, H., Tomberlin, J.K. and Yu, Z., 2011c. Bioconversion of dairy manure by black soldier fly (Diptera: Stratiomyidae) for biodiesel and sugar production. Waste Management 31: 1316-1320.

Li, S., Ji, H., Zhang, B., Tian, J., Zhou, J., and Yu, H., 2016. Influence of black soldier fly (*Hermetia illucens*) larvae oil on growth performance, body composition, tissue fatty acid composition and lipid deposition in juvenile Jian carp (*Cyprinus carpio* var. Jian). Aquaculture 465: 43-52.

Liu, Q., Tomberlin, J.K., Brady, J.A., Sanford, M.R. and Yu, Z., 2008. Black soldier fly (Diptera: Stratiomyidae) larvae reduce *Escherichia coli* in dairy manure. Environmental Entomology 37: 1525-1530.

Lock, E., Arsiwalla, T. and Waagbø, R., 2015. Insect larvae meal as an alternative source of nutrients in the diet of Atlantic salmon (*Salmo salar*) postsmolt. Aquaculture Nutrition 22: 1202-1213.

Makkar, H.P., Tran, G., Heuzé, V. and Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Animal Feed Science and Technology 197: 1-33.

Manzano-Agugliaro, F., Sanchez-Muros, M., Barroso, F., Martínez-Sánchez, A., Rojo, S. and Pérez-Bañón, C., 2012. Insects for biodiesel production. Renewable and Sustainable Energy Reviews 16: 3744-3753.

Martínez-Sánchez, A., Magaña, C., Saloña, M. and Rojo, S., 2011. First record of *Hermetia illucens* (Diptera: Stratiomyidae) on human corpses in Iberian peninsula. Forensic Science International 206(1): e76-e78.

Maurer, V., Holinger, M., Amsler, Z., Früh, B., Wohlfahrt, J., Stamer, A. and Leiber, F., 2016. Replacement of soybean cake by *Hermetia illucens* meal in diets for layers. Journal of Insects as Food and Feed 2: 83-90.

May, B., 1961. The occurrence in New Zealand and the life-history of the soldier fly *Hermetia illucens* (L.)(Diptera: Stratiomyidae). New Zealand Journal Science 4: 55-65.

Moreau, J., Benrey, B. and Thiéry, D., 2006. Assessing larval food quality for phytophagous insects: are the facts as simple as they appear? Functional Ecology 20: 592-600.

Myers, H.M., Tomberlin, J.K., Lambert, B.D. and Kattes, D., 2008. Development of black soldier fly (Diptera: Stratiomyidae) larvae fed dairy manure. Environmental Entomoloy 37: 11-15.

Nakamura, S., Ichiki, R.T., Shimoda, M. and Morioka, S., 2016. Small-scale rearing of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae), in the laboratory: low-cost and year-round rearing. Applied Entomology and Zoology 51: 161-166.

National Research Council (NRC), 1994. Nutrient requirements of poultry. National Academy Press, Washington, DC, USA.

Newton, G.L., Booram, C.V., Barker, R.W. and Hale, O.M., 1977. Dried *Hermetia illucens* larvae meal as supplement for swine. Journal of Animal Science 44: 395-400.

Newton, G.L., Sheppard, D.C., Watson, D.W., Burtle, G.J., Dove, C.R., Tomberlin, J.K. and Thelen, E.E., 2005a. The black soldier fly, *Hermetia illucens*, as a manure management/resource recovery tool. In: Proceedings of the Symposium State of the Science, Animal Manure and Waste Management, January 5-7 2005, San Antonio, TX, USA. Available at: http://tinyurl.com/klzomvn.

Newton, L., Sheppard, C., Watson, D.W. and Burtle, G., 2005b. Using the black soldier fly, *Hermetia illucens*, as a value-added tool for the management of swine manure. Report for Mike Williams, Director of the Animal and Poultry Waste Management Centre, North Carolina State University, Raleigh, NC, USA. Available at: http://tinyurl.com/mxam64v.

Nguyen, T.T., Tomberlin, J.K. and Vanlaerhoven, S., 2013. Influence of resources on *Hermetia illucens* (Diptera: Stratiomyidae) larval development. Journal of Medical Entomology 50: 898-906.

Nguyen, T.T., Tomberlin, J.K. and Vanlaerhoven, S., 2015. Ability of black soldier fly (Diptera: Stratiomyidae) larvae to recycle food waste. Environmental Entomology 44: 406-410.

Oonincx, D.G.A.B., Van Broekhoven, S., Van Huis, A. and Van Loon, J.J.A., 2015b. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PLoS ONE 10: e0144601.

Oonincx, D.G.A.B., Van Huis, A. and Van Loon, J.J.A., 2015a. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. Journal of Insects as Food and Feed 1: 131-139.

Oonincx, D.G.A.B., Van Itterbeeck, J., Heetkamp, M.J.W., Van den Brand, H., Van Loon, J.J.A. and Van Huis, A., 2010. An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. PLoS ONE 5: e14445.

Oonincx, D.G.A.B., Volk, N., Diehl, J., Van Loon, J.J.A. and Belušič, G., 2016. Photoreceptor spectral sensitivity of the compound eyes of black soldier fly (*Hermetia illucens*) informing the design of led-based illumination to enhance indoor reproduction. Journal of Insect Physiology 95: 133-139.

Rachmawati, R., Buchori, D., Hidayat, P., Hem, S. and Fahmi, M.R., 2010. Perkembangan dan kandungan nutrisi larva *Hermetia illucens* (linnaeus)(Diptera: Stratiomyidae) pada bungkil kelapa sawit. Jurnal Entomologi Indonesia 7: 28-41.

Rivers, D.B. and Dahlem, G.A., 2013. The science of forensic entomology. Wiley-Blackwell, Chichester, UK.

Sealey, W.M., Gaylord, T.G., Barrows, F.T., Tomberlin, J.K., McGuire, M.A., Ross, C. and St-Hilaire, S., 2011. Sensory analysis of rainbow trout, *Oncorhynchus mykiss*, fed enriched black soldier fly prepupae, *Hermetia illucens*. Journal of the World Aquaculture Society 42: 34-45.

Shantibala, T., Lokeshwari, R. and Debaraj, H., 2014. Nutritional and antinutritional composition of the five species of aquatic edible insects consumed in Manipur, India. Journal of Insect Science 14: 14.

Sheppard, C.D., Newton, G.L., Thompson, S.A. and Savage, S., 1994. A value added manure management system using the black soldier fly. Bioresource Technology 50: 275-279.

Sheppard, C.D., Tomberlin, J.K., Joyce, J.A., Kiser, B.C. and Sumner, S.M., 2002. Rearing methods for the black soldier fly (Diptera: Stratiomyidae). Journal of Medical Entomology 39: 695-698.

Sheppard, D.C., 1983. House fly and lesser fly control utilizing the black soldier fly in manure management systems for caged laying hens. Environmental Entomology 12: 1439-1442.

Sheppard, D.C., Newton G.L. and Burtle, G., 2008. Black soldier fly prepupae a compelling alternative to fish meal and fish oil. Public comment prepared in response to a request by the National Marine Fisheries Service Nov. 15, 2007, NOAA 15/11//2007-29/2/2008. Available at: http://tinyurl.com/l28f34a.

Simon, P., Krüger, R. and Ribeiro, P., 2011. Influence of diets on the rearing of predatory flies of housefly larvae. Arquivo Brasileiro de Medicina Veterinária e Zootecnia 63: 1414-1420.

Smetana, S., Palanisamy, M., Mathys, A. and Heinz, V., 2016. Sustainability of insect use for feed and food: life cycle assessment perspective. Journal of Cleaner Production 137: 741-751.

Spiller, D., 1964. Nutrition and diet of muscoid flies. Bulletin of the World Health Organization 341: 551-554.

Stanley-Samuelson, D.W., Jurenka, R.A., Cripps, C. Blomquist, G.J. and De Renobales, M., 1988. Fatty acids in insects: composition, metabolism, and biological significance. Archives of Insect Biochemistry and Physiology 9: 1-33.

St-Hilaire, S., Cranfill, K., Mcguire, M.A., Mosley, E.E., Tomberlin, J.K., Newton, L., Sealey, W., Sheppard, C. and Irving, S., 2007a. Fish offal recycling by the black soldier fly produces a food stuff high in omega-3 fatty acids. Journal of the World Aquaculture Society 38: 309-313.

St-Hilaire, S., Sheppard, C., Tomberlin, J.K., Irving, S., Newton, L., McGuire, M.A., Mosley, E.E., Hardy, R.W. and Sealey, W., 2007b. Fly prepupae as a feedstuff for rainbow trout, *Oncorhynchus mykiss*. Journal of the World Aquaculture Society 38: 59-67.

Surendra, K., Olivier, R., Tomberlin, J.K., Jha, R. and Khanal, S.K., 2016. Bioconversion of organic wastes into biodiesel and animal feed via insect farming. Renewable Energy 98: 197-202.

Tiu, L., 2012. Enhancing sustainability of freshwater prawn production in Ohio. Ohio State University South Centers Newsletter, Fall 2012, 11(4): 4. Available at: http://tinyurl.com/k32xfv8.

Tomberlin, J.K. and Sheppard, D.C., 2001. Lekking behavior of the black soldier fly (Diptera: Stratiomyidae). Florida Entomologist 84: 729-730.

Tomberlin, J.K. and Sheppard, D.G., 2002. Factors influencing mating and oviposition of black soldier flies (Diptera: Stratomyidae) in a colony. Journal of the Entomological Society 37: 345-352.

Tomberlin, J.K., Adler, P.H. and Myers, H.M., 2009. Development of the black soldier fly (Diptera: Stratiomyidae) in relation to temperature. Environmental Entomology 38: 930-934.

Tomberlin, J.K., Sheppard, D.C. and Joyce, J.A., 2002. Selected life-history traits of black soldier flies (Diptera: Stratiomyidae) reared on three artificial diets. Annals of the Entomological Society of America 95: 379-386.

Ushakova, N., Bastrakov, A., Kozlova, A., Ponomarev, S., Bakaneva, Y.M., Fedorovykh, Y.V., Zhandalgarova, A. and Pavlov, D., 2016. Features of the effect of a complex probiotic with *Bacillus* bacteria and the larvae of *Hermetia illucens* biomass on Mozambique tilapia (*Oreochromis mossambicus*× *O. niloticus*) and Russian sturgeon (*Acipenser gueldenstaedti*). Biology Bulletin 43: 450-456.

Van der Spiegel, M., Noordam, M.Y. and Van der Fels-Klerx, H.J., 2013. Safety of novel protein sources (insects, microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production. Comprehensive Reviews in Food Science and Food Safety 12: 662-678.

Van Huis, A., 2013. Potential of insects as food and feed in assuring food security. Annual Review of Entomology 58: 563-583.

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G. and Vantomme, P., 2013. Edible insects: future prospects for food and feed security. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, FAO Forestry Paper no. 171, 201 pp. Available at: http://www.fao.org/docrep/018/i3253e/i3253e.pdf.

Van Lenteren, J.C., 2003. Quality control and production of biological control agents: theory and testing procedures. CABI Publishing, Wallingford, UK, 327 pp.

Van Loon, J.J.A., 1991. Measuring food utilization in plant – feeding insects: toward a metabolic and dynamic approach. In: Bernays, E.A. (ed.) Insect-plant interactions, Vol. 3. CRC Press, Boca Raton, FL, USA, pp. 79-124.

Veldkamp, T., Van Duinkerken, G., Van Huis, A., Lakemond, C.M.M., Ottevanger, E. and Boekel, M.A.J.S., 2012. Insects as a sustainable feed ingredient in pig and poultry diets – a feasibility study. Report 638, Wageningen UR Livestock Production, Wageningen, the Netherlands, pp. 1-48.

Yu, G., Cheng, P., Chen, Y., Li, Y., Yang, Z., Chen, Y. and Tomberlin, J.K., 2011. Inoculating poultry manure with companion bacteria influences growth and development of black soldier fly (Diptera: Stratiomyidae) larvae. Environmental Entomology 40: 30-35.

Zhang, J., Zheng, L., Jin, P., Zhang, D. and Yu, Z., 2014a. Fishmeal substituted by production of chicken manure conversion with microorganisms and black soldier fly. In: Abstract book of the international conference 'Insects to feed the world', 14-17 May 2014, Ede, the Netherlands, pp. 14-17.

Zhang, J., Zheng, L., Jin, P., Zhang, D. and Yu, Z., 2014b. Kitchen waste converted by black soldier fly and partly substituting soymeal in chicken feed. In: Abstract book of the international conference 'Insects to feed the world', 14-17 May 2014, Ede, the Netherlands, pp. 14-17.

Zhang, J.B., Huang, L., He, J., Tomberlin, J.K., Li, J.H., Lei, C.L., Sun, M., Liu, Z.D. and Yu, Z.N., 2010. An artificial light source influences mating and oviposition of black soldier flies, *Hermetia illucens*. Journal of Insect Science 10: 202.

Zheng, L., Crippen, T.L., Holmes, L., Singh, B., Pimsler, M.L., Benbow, M.E., Tarone, A.M., Dowd, S., Yu, Z., Vanlaerhoven, S.L., Wood, T.K. and Tomberlin, J.K. 2013. Bacteria mediate oviposition by the black soldier fly, *Hermetia illucens* (L.), (Diptera: Stratiomyidae). Nature Scientific Reports 3: 2563.

Zheng, L., Crippen, T.L., Singh, B., Tarone, A.M., Dowd, S., Yu, Z., Wood, T.K. and Tomberlin, J.K., 2013. A survey of bacterial diversity from successive life stages of black soldier fly (Diptera: Stratiomyidae) by using 16s rDNA pyrosequencing. Journal of Medical Entomology 50: 647-658.

Zheng, L., Hou, Y., Li, W., Yang, S., Li, Q. and Yu, Z., 2012. Biodiesel production from rice straw and restaurant waste employing black soldier fly assisted by microbes. Energy 47: 225-229.