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) (Awonyi, 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 (Gujarat 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 fed 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.
The black soldier fly as animal feed

Fatty acid content

BSF larvae and prepupae have been found to contain 58-72% saturated fatty acids and 19-40% mono- and polyunsaturated 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 1. Content of crude protein (CP) and crude fat (CF) of black soldier fly larvae reared on different substrates.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>%CP¹</th>
<th>n</th>
<th>%CF¹</th>
<th>n</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle manure</td>
<td>42.1</td>
<td>1</td>
<td>34.8; 29.9</td>
<td>2</td>
<td>Li et al., 2011b; Newton et al., 1977</td>
</tr>
<tr>
<td>Chicken manure</td>
<td>40.1±2.5</td>
<td>3</td>
<td>27.9±8.3</td>
<td>3</td>
<td>Arango Gutiérrez et al., 2004; Li et al., 2011b; Sheppard et al., 1994; Li et al., 2011b; Manzano-Agugliaro et al., 2012; Newton et al., 2005b;</td>
</tr>
<tr>
<td>Swine manure</td>
<td>43.6; 43.2</td>
<td>2</td>
<td>26.4±7.6</td>
<td>4</td>
<td>St-Hilaire et al., 2007b;</td>
</tr>
<tr>
<td>Palm kernel meal</td>
<td>42.1; 45.8</td>
<td>2</td>
<td>27.5</td>
<td>1</td>
<td>Rachmawati et al., 2010</td>
</tr>
<tr>
<td>Restaurant waste</td>
<td>–</td>
<td>39.2</td>
<td>1</td>
<td></td>
<td>Zheng et al., 2012</td>
</tr>
<tr>
<td>Chicken feed</td>
<td>47.9±7.1</td>
<td>3</td>
<td>14.6±4.4</td>
<td>3</td>
<td>Bosch et al., 2014; Nguyen et al., 2015; Oonincx et al., 2015b;</td>
</tr>
<tr>
<td>By-products²</td>
<td>41.7±3.8</td>
<td>4</td>
<td>–</td>
<td></td>
<td>Oonincx et al., 2015b</td>
</tr>
<tr>
<td>Liver</td>
<td>62.7</td>
<td>1</td>
<td>25.1</td>
<td>1</td>
<td>Nguyen et al., 2015³</td>
</tr>
<tr>
<td>Fruits and vegetables</td>
<td>38.5</td>
<td>1</td>
<td>6.63</td>
<td>1</td>
<td>Nguyen et al., 2015³</td>
</tr>
<tr>
<td>Fish</td>
<td>57.9</td>
<td>1</td>
<td>34.6</td>
<td>1</td>
<td>Nguyen et al., 2015³</td>
</tr>
</tbody>
</table>

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.

Table 2. Amino acid content (%DM and g/16 g nitrogen¹) 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).

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Swine</th>
<th>Swine</th>
<th>Cattle</th>
<th>Chicken</th>
<th>BSF larvae¹</th>
<th>Soy meal¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alanine</td>
<td>3.02</td>
<td>2.55</td>
<td>3.7</td>
<td>2.3</td>
<td>7.7</td>
<td>4.48</td>
</tr>
<tr>
<td>Arginine</td>
<td>2.65</td>
<td>1.77</td>
<td>2.2</td>
<td>2.12</td>
<td>5.6</td>
<td>7.48</td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>3.72</td>
<td>3.04</td>
<td>4.6</td>
<td>1.36</td>
<td>11.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Cystine</td>
<td>–</td>
<td>0.31</td>
<td>0.1</td>
<td>0.32</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Glycine</td>
<td>2.28</td>
<td>2.07</td>
<td>2.9</td>
<td>2.31</td>
<td>–</td>
<td>4.25</td>
</tr>
<tr>
<td>Glutamic acid</td>
<td>3.78</td>
<td>3.99</td>
<td>3.8</td>
<td>2.75</td>
<td>10.9</td>
<td>19.3</td>
</tr>
<tr>
<td>Histidine</td>
<td>1.18</td>
<td>0.96</td>
<td>1.9</td>
<td>1.16</td>
<td>3.0</td>
<td>2.53</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>2.03</td>
<td>1.51</td>
<td>2.0</td>
<td>1.55</td>
<td>5.1</td>
<td>5.04</td>
</tr>
<tr>
<td>Leucine</td>
<td>3.1</td>
<td>2.61</td>
<td>3.5</td>
<td>2.6</td>
<td>7.9</td>
<td>8.04</td>
</tr>
<tr>
<td>Lysine</td>
<td>2.62</td>
<td>2.21</td>
<td>3.4</td>
<td>2.14</td>
<td>6.6</td>
<td>6.39</td>
</tr>
<tr>
<td>Methionine</td>
<td>0.74</td>
<td>0.83</td>
<td>0.9</td>
<td>0.78</td>
<td>2.1</td>
<td>1.17</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>2.00</td>
<td>1.49</td>
<td>2.2</td>
<td>1.53</td>
<td>5.2</td>
<td>5.05</td>
</tr>
<tr>
<td>Proline</td>
<td>2.39</td>
<td>2.12</td>
<td>3.3</td>
<td>2.27</td>
<td>6.6</td>
<td>5.51</td>
</tr>
<tr>
<td>Serine</td>
<td>1.68</td>
<td>1.47</td>
<td>0.1</td>
<td>2.8</td>
<td>3.1</td>
<td>4.85</td>
</tr>
<tr>
<td>Threonine</td>
<td>1.78</td>
<td>1.41</td>
<td>0.6</td>
<td>1.87</td>
<td>3.7</td>
<td>3.93</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>–</td>
<td>0.59</td>
<td>0.2</td>
<td>0.63</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>3.08</td>
<td>2.38</td>
<td>2.5</td>
<td>2.62</td>
<td>6.9</td>
<td>3.64</td>
</tr>
</tbody>
</table>

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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 (CaCO₃) 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).

### 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).

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

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

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., 2005b). 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
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 niloticus*; (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 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.

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**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).**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Poultry manure&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Swine manure</th>
<th>Chicken feed</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>5.2; 7.8</td>
<td>5.36</td>
<td>3.14</td>
<td>2.41</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.7; 1.5</td>
<td>0.88</td>
<td>1.28</td>
<td>0.91</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.37; 0.39</td>
<td>0.44</td>
<td>0.79</td>
<td>0.45</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.15</td>
<td>0.13</td>
<td>0.27</td>
<td>0.23</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.6; 0.7</td>
<td>1.16</td>
<td>1.96</td>
<td>1.17</td>
</tr>
<tr>
<td>Iron</td>
<td>0.11; 0.14</td>
<td>0.08</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.01; 0.013</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Copper</td>
<td>0.001</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.02; 0.06</td>
<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
</tr>
</tbody>
</table>

<sup>1</sup> If n=2, individual values are stated, separated by a semicolon.

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The black soldier fly as animal feed

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.

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

<table>
<thead>
<tr>
<th>Abiotic factor</th>
<th>Min.</th>
<th>Optimal</th>
<th>Max.</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>12</td>
<td>26-27</td>
<td>36</td>
<td>Booth and Sheppard, 1984; Holmes, 2010; Holmes et al., 2016;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sheppard et al., 1994; Tomberlin et al., 2009</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>25</td>
<td>60-70</td>
<td>99</td>
<td>Gobbi, 2012; Holmes et al., 2012; Tomberlin and Sheppard, 2002</td>
</tr>
<tr>
<td>Substrate moisture (%)</td>
<td>40</td>
<td>52-70</td>
<td>70</td>
<td>Fastchurochim et al., 1989; Furman et al., 1959; Tomberlin et al., 2002</td>
</tr>
<tr>
<td>Light intensity 1</td>
<td>60</td>
<td>135-200</td>
<td>-</td>
<td>Alvarez, 2012; Holmes, 2010; Tomberlin and Sheppard, 2002; Zhang et al., 2010</td>
</tr>
</tbody>
</table>

1 Light intensity is expressed in μmol/m²/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 (Oninnx et al., 2016).

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 prepupa, reach the prepupal stage in two weeks at 30°C (Furman et al., 1959). Prepupa 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
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; 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/cm².

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.

<table>
<thead>
<tr>
<th>Life-history or performance trait</th>
<th>n²</th>
<th>Mean±SD</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larval developmental time (days)</td>
<td>13</td>
<td>24.6±6.2</td>
<td>Diener et al., 2011; Gobbi, 2012; Li, 2014; Nguyen et al., 2013; Oonincx et al., 2015b; Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Pupal developmental time (days)</td>
<td>8</td>
<td>14.8±6.8</td>
<td>Gobbi, 2012; Nguyen et al., 2013; Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Total cycle (days)</td>
<td>8</td>
<td>40.2±6.4</td>
<td>Gobbi, 2012; Nguyen et al., 2013; Tomberlin, 2001</td>
</tr>
<tr>
<td>Larval survival rate (%)</td>
<td>5</td>
<td>89.4±9.4</td>
<td>Gobbi, 2012; Li, 2014; Oonincx et al., 2015b; Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Pupal survival rate (%)</td>
<td>1</td>
<td>91</td>
<td>Gobbi, 2012</td>
</tr>
<tr>
<td>Larval weight (g FM)</td>
<td>6</td>
<td>0.158±0.02</td>
<td>Li, 2014; Nguyen et al., 2013; Oonincx et al., 2015b; Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Larval weight (g DM)</td>
<td>1</td>
<td>0.044</td>
<td>Li, 2014</td>
</tr>
<tr>
<td>Prepupal weight (g FM)</td>
<td>5</td>
<td>0.105±0.005</td>
<td>Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Prepupal weight (g DM)</td>
<td>3</td>
<td>0.037±0.004</td>
<td>Diener et al., 2011</td>
</tr>
<tr>
<td>Pupal weight (g FM)</td>
<td>3</td>
<td>0.150±0.03</td>
<td>Gobbi, 2012</td>
</tr>
<tr>
<td>Adult weight (g FM)</td>
<td>3</td>
<td>0.053±0.01</td>
<td>Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Adult weight (g DM)</td>
<td>1</td>
<td>0.021</td>
<td>Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>Adult length (mm)</td>
<td>1</td>
<td>15.8</td>
<td>Gobbi, 2012</td>
</tr>
<tr>
<td>Adult longevity (days)</td>
<td>3</td>
<td>9.4±0.2</td>
<td>Tomberlin and Sheppard, 2001</td>
</tr>
<tr>
<td>ECI DM (%)</td>
<td>4</td>
<td>17.6±6.3</td>
<td>Diener et al., 2011; Li, 2014; Oonincx et al., 2015b</td>
</tr>
<tr>
<td>ECD DM (%)</td>
<td>3</td>
<td>32.1±4.3</td>
<td>Diener et al., 2011; Li, 2014</td>
</tr>
<tr>
<td>FCR</td>
<td>1</td>
<td>1.8</td>
<td>Li, 2014</td>
</tr>
<tr>
<td>Larval DM content (%)</td>
<td>3</td>
<td>36±1.8</td>
<td>Diener et al., 2011; Oonincx et al., 2015b</td>
</tr>
</tbody>
</table>

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 in Table 7.

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

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

$^1$ 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 prepupa 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 prepupa 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 prepupa 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 cm² can be calculated (min. 0.1 and max. 3.33 larvae/cm²). Sheppard et al. (2002) suggest a density of 2.5 larvae per cm² 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

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BSF larvae fed human faeces at different densities (0.02, 0.2, and 0.31 larva/cm²), 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 pupae 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 feedstuffs 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 pupae. 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 ammonotelic 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 within 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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