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Conversion of organic resources by black soldier fly larvae: Legislation, efficiency and environmental impact

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ABSTRACT

To meet the projected substantial growth in the global demand for meat, we are challenged to develop additional protein-rich feed ingredients while minimizing the use of natural resources. The larvae of the black soldier fly (BSF) have the capacity to convert low-value organic resources into a high quality protein source for pigs, chickens and fish and as such may increase both the productivity and the efficiency of the food chain. The aim of this study was to assess the environmental opportunities of BSF larvae reared on different sources using up to date literature data on the efficiency of BSF larvae in converting such resources into biomass. The current EU legislative framework was used to classify the various resources for rearing insects. Data of forty articles published until 1 September 2017 were used, reporting on in total 78 (mixtures of) resources used for growing BSF larvae. Data on the resource conversion efficiency on dry matter (DM) and N basis was presented in 11 and 5 studies, evaluating 21 and 13 resources, respectively. Resources studied included food and feed materials (A, n = 8 resources), foods not intended (anymore) for human consumption (B1, n = 4), and residual streams such as food waste (D, n = 2), and animal manure (E, n = 7). Conversion efficiency varied from 1.3 to 32.8% for DM and from 7.4 to 74.8% for N. Using life cycle assessment, our environmental results showed that resources within the legal groups (i.e. A and B1) that are, at the moment, not allowed in EU as animal feed have in general a lower impact in terms of global warming potential, energy use, and land use. On a per kg protein basis, BSF larvae reared on a resource that contains food (e.g. sorghum) and feed (e.g. dried distillers grains with solubles) products generally have higher environmental impacts than conventional feed protein sources (fishmeal and soybean meal). Using insects as feed, therefore, has potential to lower the environmental impact of food production but a careful examination of the resource is needed in terms of environmental impact, safety and economics.

1. Introduction

For assuring food security within the planet's carrying capacity, new ways are required to increase protein production while minimizing the use of natural resources (Godfray et al., 2010; Foley et al., 2011). As the demand for meat is projected to grow with 76% (2005/2007–2050, Alexandratos and Bruinsma, 2012), there is in particular a need to find additional protein-rich feed ingredients as well as alternatives for those associated with a high environmental impact such as soybean meal (Veldkamp et al., 2012; van Huis et al., 2013). Insects have been proposed to increase both the productivity and the efficiency of the food chain (van Huis et al., 2013). Research on using insects as feed is rapidly evolving and several reviews have recently been published on their nutritional value, potential organic resources, and food safety (Veldkamp et al., 2012; van Huis, 2013; Barroso et al., 2014; Makkar et al., 2014; Pastor et al., 2015; Barragan-Fonseca et al., 2017; Testa et al., 2017; Varelas and Langton, 2017; van der Fels-Klerx et al., 2018). In particular the

Abbreviations: BSF, black soldier fly; DM, dry matter; EFSA, European Food Safety Authority; EU, European Union; GHG, greenhouse gas; GWP, global warming potential; LCA, life cycle assessment; N, nitrogen; PAPs, processed animal proteins.

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larvae of the black soldier fly (*Hermetia illucens*, BSF[1]) receive considerable interest as these have the ability to upcycle various residual organic resources (Pastor et al., 2015) into protein-rich biomass fit as feed ingredients for pigs, chickens and fish (e.g. Newton et al., 1977; Bondari and Sheppard, 1981; De Marco et al., 2015).

From an environmental viewpoint, only a few studies quantified the impact of BSF larvae (Smetana et al., 2016; Salomone et al., 2017). Current literature showed that the resource used to rear BSF larvae affects the environmental impact: BSF larvae fed with cattle manure and municipal waste seem to have a relatively lower environmental impact than those fed with e.g. beet pulp (Smetana et al., 2016). It is, however, unclear which resources or groups of resources have potential to reduce the environmental impact and how this relates to the legal status of using those biomass streams as a resource to feed larvae. Although in the European Union (EU) it is currently not allowed to use insects as feed that are fed on resources containing manure or waste, it is important to understand the potential of BSF larvae for improving the productivity and resource use efficiency of our food system. Furthermore, resources under study may already have applications as livestock feed ingredients (e.g. beet pulp), which underlines the need for a clear differentiation and categorisation of resources for applications within (i.e. as food or feed) and outside the food chain. As the choice of organic resources for BSF larvae production is crucial for the economics, environmental footprint and safety of the products, the research on the suitability of organic resources for BSF larvae production has been rapidly growing over the years. Resources may differ greatly in their impact on larval development time, biomass yield and quality, associated emissions and residual matter (frass and exuvia). More data are becoming available on how efficient BSF larvae actually convert the nitrogen (N) from resources into nitrogenous biomass. These data allow more extensive assessments of the environmental impact of BSF larvae as an alternative protein-rich feed ingredient. The aim of this study was to assess the environmental opportunities of insects reared on different organic biomass resources and relate their potential to the current EU legislation framework. We used a cross-disciplinary approach to cover areas of law, animal sciences and environmental sciences simultaneously to critically assess our current understanding of the concept of using BSF larvae to make our food system more productive and sustainable.

2. Method

To assess the environmental opportunities of different organic resources and relate their potential to the current legislation framework, we i) classified organic resources according to EU legislation (2.1); ii) analysed literature data on organic resources used as feed for BSF larvae and, where possible, calculated the feed conversion efficiency (2.2); iii) assessed the environmental impact of BSF larvae reared on these organic resources (2.3).

2.1. Legal classification of organic resources and safety

In the EU, insects reared for food or feed fall under the definition of 'farmed animal' (Article 3.6 of Regulation (EC) No 1069/2009), which has certain consequences for the permission to use a feed (organic resource or substrate) for a farmed animal. General rules for all feed in the EU, including that for insects, are that it has to be (a) safe, and (b) it does not have a direct adverse effect on the environment or animal welfare (Article 4 Regulation (EC) No 767/2009 and Article 15 of Regulation (EC) No 178/2002). In addition, there are requirements for feed hygiene (Regulation (EC) No 183/2005) and the maximum contents of certain undesirable substances in animal feed (Directive, 2002/32/EC). We build on the demarcation between insect feeding source options, as previously defined by the European Food Safety Authority (EFSA, 2015), and used it for the classification of resources evaluated for insect rearing. The legal status (allowed or not allowed) and justification for this status are presented in Table 1. A more extensive description of the background of group of insect feeding source options can be found in the supplementary material.

2.2. Literature review of bioconversion studies

There is a growing number of studies that focus on the use of BSF larvae to convert organic resources with purposes that relate to feed and biofuel production as well as waste management (Table S1). We performed a literature review to create an overview of organic resources used as feed and feed conversion efficiency of BSF larvae. Articles published in peer-reviewed scientific journals before September 1 2017 were retrieved from online databases (Scopus, Google Scholar) using initial search terms '*Hermetia illucens*', 'waste', and 'conversion'. We extended our search for relevant articles via checking the reference list and citations in each article. Though various studies reported conversion efficiencies on fresh matter basis (insect biomass collected divided by the amount diet provided in %), obtained efficiencies cannot be directly compared as considerable variation was present in the moisture levels of the diets (12.3% in Lardé (1990) to 31.7% in Oonincx et al. (2015a)) and the larvae (17.9% in Tschirner and Simon (2015) to 38.8% in Finke (2013)). With two resources both being converted for 20% on fresh basis, on dry matter (DM) basis, one may be converted with an efficiency of only 11% whereas for the other this would be 63%. We therefore focussed on the conversion efficiencies on DM and N basis as is usual in insect feed conversion studies (van Loon, 1991) and subsequently used these to calculate the environmental impact.

Forty articles evaluated in total 78 (mixtures of) resources (Table S1 in supplementary material). BSF larvae were in particular fed with animal and human manure (Group E and Group G, respectively), but also different types of food waste and various animal feed materials have been tested (D and A, respectively). Few studies, however, evaluated the suitability of gardening and forest material (E). Conversion efficiency on DM and N basis was reported or could be calculated from data presented in 11 and 5 studies (Table 2), which collectively evaluated 21 and 13 organic resources, respectively (Fig. 1). As several resources were fed as mixtures with different ratios (Liland et al., 2017; Rehman et al., 2017a, 2017b; Tinder et al., 2017), resources were tested twice (Tinder et al., 2017), or fed at different feeding levels (Parra Paz et al., 2015), the total number of data points exceeds the number of resources tested. In total, our dataset contained 62 values for DM conversion and 34 values for N conversion. The studies differed in amount of resource provided per larva and the number and age of the larvae at the start of the trial (Table 2). The rearing temperature (~28 °C) and relative humidity (~70%) were relatively similar among studies. Timing of harvest differed among studies, varying from 5 to 6 instar and 16 day-old BSF larvae to harvesting when one larva, 50% or all larvae were in the prepupal phase.

The DM conversion efficiency varied considerably among the 21 resources from 1.3% for vegetal refuse and fruits (Parra Paz et al., 2015) to 32.8% for processed Chinese restaurant waste (Zheng et al., 2012) (Fig. 1). The N conversion efficiency in the 13

[1] Abbreviations: BSF, black soldier fly; DM, dry matter; EC, European Parliament and Council; EFSA, European Food Safety Authority; EU, European Union; GHG, greenhouse gas; GWP, global warming potential.

Table 1
Groups of insect feeding source options and their legal status.

Group	Description	Legal status	Legal justification
A	Animal feed materials according to the EU catalogue of feed materials and authorized as feed for food producing animals.	✓	Regulation (EU) No 68/2013
B1	Food produced for human consumption, but which is no longer intended for human consumption for reasons such as expired use-by date or due to problems of manufacturing or packaging defects. Excluding meat and fish (processed animal proteins, PAPs).	✓	Former foodstuffs of vegetable origin: • Regulation (EU) No 68/2013 Permitted former foodstuffs of Animal origin (non-PAPs): • Regulation (EU) No 142/2011, Annex X, Chapter II, Section 10
B2	Meat and fish produced for human consumption, but which is no longer intended for human consumption for reasons such as expired use-by date or due to problems of manufacturing or packaging defects.	X	• Regulation (EC) No 999/2001, Article 7(2) • Regulation (EU) No 142/2011, Annex X, Chapter II, Section 10 • Regulation (EC) No 1069/2009, Article 10(f)
C	By-products from slaughterhouses (hides, hair, feathers, bones etc.) that do not enter the food chain but originate from animals fit for human consumption.	X	• Regulation (EC) No 999/2001, Article 7(2) • Regulation (EC) No 1069/2009, Article 10(b)
D	Food waste from food for human consumption of both animal and non-animal origin from restaurants, catering and households.	X	• Regulation (EC) No 1069/2009, Article 11(1)b
E	Animal manure and intestinal content.	X	• Regulation (EC) No 1069/2009, Article 9(a)
F	Other types of organic waste of vegetable nature such as gardening and forest material.	✓/X	• Regulation (EC) No 767/2009, Annex III • Regulation (EC) No 68/2013 • Directive 2008/98/EC
G	Human manure and sewage sludge.	X	• Regulation (EC) No 767/2009, Article 6 • Directive 91/271/EEC • Directive 86/278/EEC

resources varied from 7.4% for chicken and dairy manure (Oonincx et al., 2015b) to 74.8% for sorghum (Tinder et al., 2017). Next to the variation in experimental set-up and rearing conditions (Table 2), it should be noted that testing of multiple resources was suboptimal (see Discussion) and, therefore, results into an underestimate of the conversion potential of the BSF larvae.

2.3. Environmental assessment

Life cycle assessment (LCA) was applied according to ISO standards (2006b; a) to assess the environmental impact of larvae meal production. LCA is an internationally accepted and standardised holistic method to evaluate the environmental impact during the entire production chain (Guinée et al., 2002; Baumann and Tillman, 2004). LCA includes four phases, being goal and scope definition, inventory analysis (data collection), impact assessment (encompasses classification and characterization of the emissions and resources used), and interpretation of results.

Goal and scope definition. The goal of this study was to assess the environmental impact of the production of fresh BSF larvae reared on different organic biomass resources. The functional unit was a kg of fresh larvae and to compare it with other feed ingredients we also expressed the impact per kg of larval protein.

Inventory analysis. Data related to the required inputs and outputs to produce one kg of fresh larvae were obtained from literature (see section 2.2). In this study we only accounted for the processes that are related to the environmental potential of the different resources: production of the resource, processing of the resource, larvae rearing, and larvae/resource separation. We assumed that the rearing plant is situated in The Netherlands. Not all studies identified in section 2.2 (see Table 2) contained the data needed to perform the LCA and were therefore excluded from the assessment of the environmental impact. Diener et al. (2011) was excluded because no data were provided on the feeding level. Data of BSF larvae production based on feeding seaweed (Liland et al., 2017) were not used as seaweed production technology is currently under development and accurate estimates of the associated environmental impact are unavailable. The control diet, i.e. processed wheat, however, was used in the analyses. Data from Tschirner and Simon (2015) and Oonincx et al. (2015b) were not used as larvae did show unacceptable growth due to feeding regime and the feeding substrate was not well enough defined. Tinder et al. (2017) evaluated (mixtures) of feeding substrates twice and we used the results of trail A. For the study of Parra Paz et al. (2015), the larvae to feeding substrate ratio resulting in the highest conversion was used in the calculations.

Impact assessment. During the life cycle of a product, two types of environmental impacts are considered: emissions of pollutants and use of resources, such as land or fossil-fuels (Guinée et al., 2002). We assessed greenhouse gas (GHG) emissions, energy use, and land use. These impacts were chosen because the livestock sector contributes significantly to both land use and climate change worldwide (Steinfeld et al., 2006). Furthermore, energy use was used as it influences global warming potential (GWP) considerably and plays an important role in the rearing of insects (van Zanten et al., 2015). Land use was recalculated to square meters and expressed in m^2 kg of fresh larvae, whereas energy use was expressed in mega joules of primary energy (MJ). The major GHGs related to livestock production (Steinfeld et al., 2006) were included in this study: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These GHGs were summed up based on their equivalence factors in terms of CO_2 (100 years' time horizon) kg of fresh larvae: i.e. carbon dioxide (CO_2), biogenic methane (CH_4, bio): 28 kg CO_2-eq/kg, fossil methane (CH_4, fossil): 30 kg CO2-eq/kg; and nitrous oxide (N_2O): 265 kg CO_2-eq/kg. Data related to emissions and resources were mainly obtained from databases and literature

Table 2
Rearing conditions and timing of harvest for studies evaluating dry matter (DM) and N conversion of organic resources by black soldier fly larvae.

Rearing							Harvest	Conversion		Reference
Feed type (group[1])	Amount of feed	Larvae	Age	Temp.	Light	RH	Life stage	DM	N	
	(g FM)	(number)	(d)	(°C)	(h)	(%)		(%)	(%)	
Municipal organic waste (D)	NR	NR	0	31.8	NR	NR	Prepupae	+	−	Diener et al. (2011)
Dairy cow manure (E)	1249	~1200	10	27	Env.	60–75	Prepupae	+	+	Li et al. (2011)
Solid residual fraction of defatted raw waste from Chinese restaurants (D)	1000	1000	8	26–29	NR	65–75	50% Prepupae	+	−	Zheng et al. (2012)
Four mixtures of spent grains, beer yeast, cookie remains, bread remains, potato steam peelings, beet molasses (all A)	13–19	100	0	28	12	70	1st Prepupae	+	+	Oonincx et al. (2015a)
Dairy cow manure (E), pig manure (E), chicken manure (E)	111–165	100	0	27	12	70	1st Prepupae	+	+	Oonincx et al. (2015b)
Vegetal (plantain, potato, cabbage) and fruit (banana, papaya) refuse (A)	96–1194	59–333	NR	26–28	NR	NR	50% Prepupae	+	−	Parra Paz et al. (2015)
Wheat middlings (A), DDGS (A), beet pulp (A)	19,200–20,000	~16,000	8	NR	NR	NR	5-6 instar larvae	+	+	Tschirner and Simon (2015)
Seaweed (A)	3000-12,000	~15,000	8	30	0	65	16 d old larvae	+	−	Liland et al. (2017)
Dairy cow manure (E), chicken manure (E), and mixtures thereof (E)	1000	1000	6	27	NR	60–70	1st Prepupae	+	−	Rehman et al. (2017a)
Soybean curd residue (A), dairy cow manure (E), and mixtures thereof (E)	1000	1000	6	27	NR	60–70	1st Prepupae	+	−	Rehman et al. (2017b)
Sorghum (A), cowpeas (A), and mixtures thereof (A)	93–297	300	4	28 ± 2	14	70	Prepupae	+	+	Tinder et al. (2017)

Abbreviations: Temp., temperature; RH, relative humidity; FM, fresh matter; NR, not reported; DDGS, dried distillers grains with solubles.
[1]Groups of insect feeding source options according to legislation in European Union (see Table 1).

and are described in more detail in the next paragraphs. In case of a multifunctional process (e.g. production of soybean oil and meal), economic allocation was used, which is the partitioning of environmental impacts between co-products based on the relative economic value of the outputs (Guinée et al., 2002).

2.3.1. *Production of the resource*

As illustrated in Fig. 1 feeding substrates consisted out of different organic products in different proportions. The environmental impacts of most biomass resources within each resource were derived from the ecoinvent database v3.3 (Table 3). Besides those biomass resources, laying hen manure and dairy cattle manure were used as a feeding source. As there was no specific data available about the use of manure for insect rearing, it was assumed that emissions for using manure were equal to emissions from a laying hen and dairy farm. We therefore accounted for CH_4 and direct and indirect N_2O emissions during the handling and storage of chicken (laying hen) and dairy cattle manure (used as a feeding source).

To estimate emission of CH_4 and direct and indirect emission of N_2O from manure, a tier 2 approach was used based on country-specific data (Coenen et al., 2018; van Bruggen, 2018) and IPCC default values (IPCC, 2006) (an emission factor of 0.03 CH_4 kg per laying hen per year and 37.69 CH_4 kg per dairy cow per year, for direct N_2O 0.76 kg N excretion per laying hen per year and 144 kg N excretion per dairy cow per year, 17.5 kg manure per laying hen per year and 28,000 kg per dairy cow per year, and a default emission factor of 0.1, for indirect N_2O: volatilisation 40% and an emission factor of 0.01).

2.3.2. *Resource processing*

Before the organic resources can be used as feeding substrate, processing is required. The resource is mixed to create a homogeneous distribution of the different resources, and grinding is done to create a texture that leads to an efficient digestion by the larvae (Parra Paz et al., 2015). Furthermore, drying and hydration processing were needed to obtain the optimal moisture content (normally around 70%) of the feeding substrates. The impact of grinding the material was assumed to be similar to the grinding of 1 kg of grains (ecoinvent). For drying, we accounted for the removal of water per kg based on ecoinvent and adapted this to each case.

2.3.3. *Larvae rearing*

Larvae were kept at a temperature of 28 °C, a relative humidity of approximately 70% and were fully grown after 16 days. A constant ventilation is needed to provide oxygen and remove CO_2 and to avoid heat accumulation, which can occur due to high larval densities. Light is not needed during larval development. The density of the larvae per crate was based on Liland et al. (2017), amounting up to a density of about 830,000 larvae/m^3. Energy needed for heating approximately one m^3 of air to 28 °C was about 0.57 kWh per day, based on data obtained during experiments in climate chambers at the Laboratory of Entomology (Wageningen University & Research, Wageningen, The Netherlands).

2.3.4. *Larvae/resource separation*

To harvest the larvae, the (remaining) resource will be sieved and we assumed that the energy use of a sieving machine for nuts was similar as no other data was available (Brand: Yong Qing, Model: XZS). The energy use to sieve one kg of larvae was about 0.025 kWh.

2.3.5. *Conversion to per kg protein basis*

To express environmental impact per kg larval protein, the DM and N values presented in the studies were used. For Tinder et al.

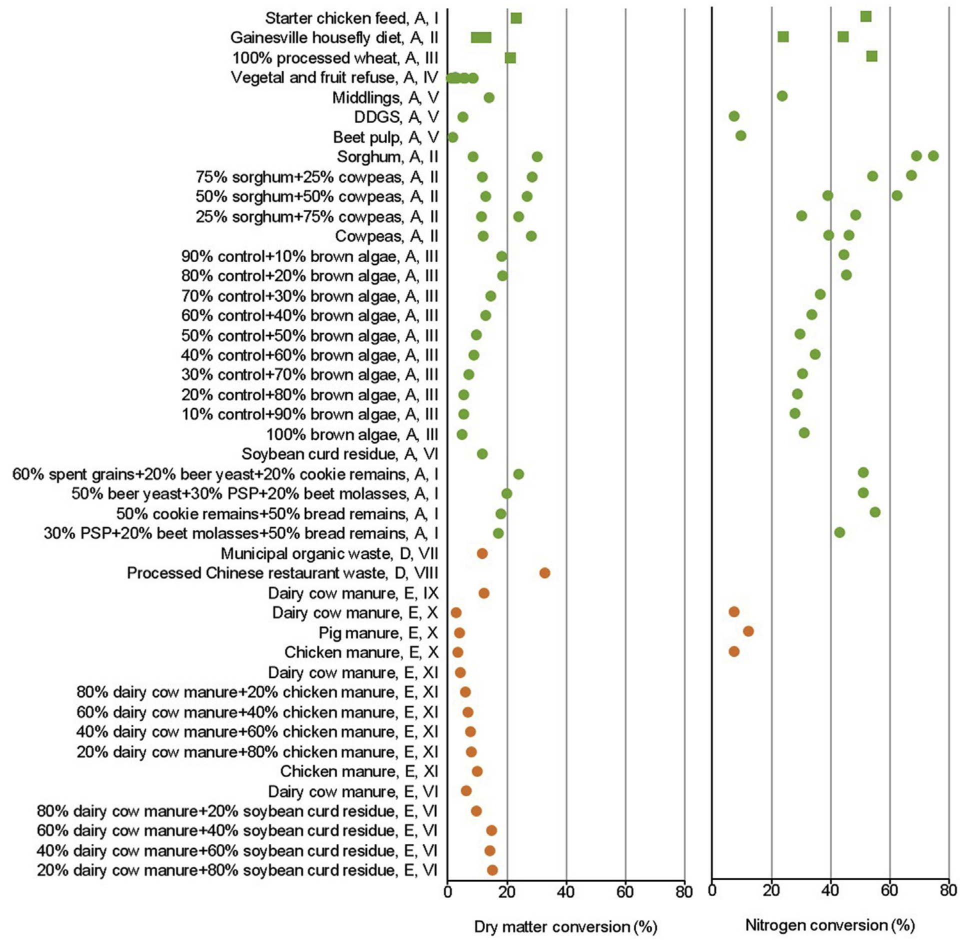

Fig. 1. Dry matter (DM) and nitrogen (N) conversion efficiency[1] for various (mixtures of) organic resources[2] as reported or calculated from data provided in scientific literature[3]. [1]Conversion efficiency was defined as collected insect biomass divided by amount of diet provided, both in grams DM or N.[2]Groups of resources are indicated (A to E) as well as their legal status according to the European Union (allowed in green, not allowed in orange; for details see Table 1). The first three resources (data points depicted as squares) were used as reference resources in the studies. For some studies, multiple data points exist per diet, which reflects replication of the study or variations in feeding level (i.e. g diet provided per larva).[3]References, I, Oonincx et al. (2015a); II, Tinder et al. (2017); III, Liland et al. (2017); IV, Parra Paz et al. (2015) with the vegetal refuse and fruits consisting out of 21% plantain, 17% potato, 20% banana, 6% papaya and 36% cabbage; V, Tschirner and Simon (2015); VI, Rehman et al. (2017b); VII, Diener et al. (2011); VIII, Zheng et al. (2012) with processed material being the solid residual fraction of defatted raw waste from Chinese restaurants; IX, Li et al. (2011); X, Oonincx et al. (2015b); XI, Rehman et al. (2017a).

(2017) the DM content and for Parra Paz et al. (2015) the DM and N contents of the larvae were not presented and the average DM and N presented in Oonincx et al. (2015a) were used (33.7 and 7.2%, respectively). For the studies of Rehman et al. (2017a, 2017b) a N content on DM basis of 6.7% (Newton et al., 1977) was used. To convert from N to protein, a conversion factor of 4.7 was used (Janssen et al., 2017).

3. Results

Table 4 presents the environmental impact per kg of fresh larvae per feeding substrate group. Our results show that the environmental impact indeed largely depends on the type of resource used. Of the different processes, the main environmental impact related to the production of the resource, followed by processing of the resource, heating and lastly the energy needed for the separation of the larvae from the (remaining) resource (Supplementary material, Fig. S1). Although similar conclusions were found in other studies (Oonincx and de Boer, 2012; Smetana et al., 2016; Halloran et al., 2017), the relative contribution of each process can easily shift depending on the type of resource used. Most data were available for resources of Group A and Group E (10 and 12 values, respectively). Group A is the group that is legally allowed and therefore represents the current situation. We do see, however, large differences in the environmental impact within Group A (Table 4). In general, we can conclude that resources that contain products that can also be used for human consumption (food), like sorghum and cowpeas (Tinder et al., 2017), result in the highest environmental impact (Fig. 2 and Supplementary material Table S2). Resources that include co-products or former foodstuffs generally used as feed, e.g. cookie remains tested in Oonincx et al. (2015a), have a lower environmental impact in terms of GWP and energy use. Resources that contain organic residual materials, i.e. products that are not used as food or feed, such as food waste (Zheng et al., 2012) or manure (Rehman et al., 2017a), result general in the lowest environmental impact when expressed on per kg fresh larvae (Table 4) but not always when expressed on per kg protein basis (see Fig. 2 and Table S2). This relates to the conversion factor used to express the impact on a per kg protein basis, which was higher for these resources as mainly DM content was relatively low (i.e. on average 37.7% in Oonincx et al. (2015a) and 21.9% in Rehman et al. (2017a, 2017b)).

BSF larvae have a high crude protein content and can replace fishmeal and soybean meal in conventional livestock feeds. In

Table 5 we compared the environmental impact of fishmeal and soybean meal with the average environmental impact of larvae reared on resources containing food ingredients, feed ingredients and residual resources. Our results show that BSF larvae reared on resources containing residual resources offer potential to reduce the environmental impact in terms of energy use and land use but not necessarily for GWP. While BSF larvae reared on resources containing food or feed ingredients will most likely increase the environmental impact. The control feeding substrates, i.e. processed wheat (Liland et al., 2017) in the food class and starter chicken feed (Oonincx et al., 2015a) and Gainesville diet (Tinder et al., 2017) in the feed class, impacted the averages of the environmental impact categories for these classes (see Fig. 2). Excluding these feeding substrates would result in a larger differences between the averages for these two categories being, respectively, 22 and 3 kg CO_2-eq, 192 and 43 MJ, and 79 and 0 m^2 per kg protein.

4. Discussion

4.1. Environmental impact

The BSF larvae have been suggested to play a role in promoting a circular economy via upcycling of resources currently lost or not efficiently used in the food chain and acting as a protein-rich feed ingredient for the livestock and aquaculture sectors (Makkar et al., 2014; Henry et al., 2015). We assessed the environmental opportunities of insects reared on different organic biomass resources described in the scientific literature and related their potential to the current EU legislation framework. For a long time, the use of insects as food and feed was not allowed at all but this situation has changed and since half a decade insects are gaining more and more interest at the European level. In the summer of 2017, EU has authorized the inclusion of insects in fish feed and it is expected that approval of insect processed animal proteins (PAPs) to be fed to pigs and poultry is expected for 2019 (Andriukaitis, 2017). Next to a wider application of BSF larvae as a feed ingredient, regulations for the resources to produce the insects will determine the degree to which BSF larvae can be incorporated in the food system to make it more efficient and productive. At the EU level it is currently not allowed to use insects as food or feed that are fed on resources containing manure or waste due to safety regulations. At present, resources allowed for BSF larvae production are those that are also fit for feeding pigs and poultry. From an environmental perspective, it is crucial to consider BSF larvae production from residual organic resources that are not considered as food or feed materials and currently left unused in the food system. Our findings clearly show that only if we use residual streams as a feeding substrate, BSF larvae production can result into environmental benefits (lower GHG emissions and especially lower land use) compared to conventional protein-rich feed ingredients with a high environmental impact. The studies of Smetana et al. (2016) and Salomone et al. (2017) found similar results with high variations. Smetana et al. (2016) found values between 2.8 and 31.2 kg CO_2-e and between 0.06 and 14.5 m^2 per kg of protein larvae fed on municipal waste and beet-pulp, respectively. Salomone et al. (2017) found a value of 2.10 kg CO_2-e and of 0.05 m^2 per kg of protein, from larvae fed on municipal weight (Salomone et al., 2017). Although GHG emissions can be reduced if residual streams are used, it should be noted that there is limited information available related to potential emissions from the resource or larvae which might have a substantial impact on the total GHG emissions. Mertenat et al. (2019) measured CH_4 and N_2O emissions during BSF rearing on food waste and concluded that CH_4 emissions were low along the rearing period while N_2O did not differ significantly from the ambient, but tends to increase temporally after feeding events. More research is needed on BSF N_2O emissions. Besides the direct environmental impact that we assessed (as our aim was to compare the different resources) one could also consider indirect consequences and a broader range of environmental impacts. The use of organic resources can, for example, result in a competition with food, feed, fuel, and fertiliser production for natural resources. The study of van Zanten et al. (2015) showed, for example, that using food waste as feeding substrate for housefly larvae results in a direct competition with bioenergy production, increasing the use of fossil fuels and subsequently resulted in a higher environmental impact. Using residual streams with a limited application (e.g. manure in The Netherlands due to the surplus) is therefore recommended to avoid this competition. This competition can also be reduced by using residual streams as efficiently as possible, for example, using the remaining material as fertiliser or to produce bioenergy. Before BSF larvae production is implemented in practice more environmental assessment studies are needed to get a better understanding about the role of BSF larvae within a sustainable food system.

Table 3
Environmental impact of resources[1] for global warming potential (GWP, kg CO_2-eq), energy use (MJ) and land use (m^2) per kg of product unless defined differently.

Resource	GWP	Energy use	Land use
Alfalfa	0.38	2.04	1.69
Beer yeast	0.47	7.30	0.00
Beet molasses	0.33	3.70	0.22
Beet pulp	0.37	5.60	0.00
Bread remains*	0.00	0.00	0.00
Cookie remains*	0.00	0.00	0.00
Corn meal	0.64	6.50	1.20
Cowpea	0.67	5.51	3.20
Dried distillers grains with solubles (DDGS)	0.30	4.60	0.00
Electricity 1 kWh	0.75	11.80	0.01
Grain semolina	0.52	3.26	1.19
Maize	0.60	5.20	1.30
Manure chicken	0.04	0.00	0.00
Manure dairy	0.04	0.00	0.00
Palm kernel expeller	0.55	3.20	0.30
Palm oil	3.90	11.00	3.00
Potato steam peeling*	0.00	0.00	0.00
Rapeseed expeller	0.53	3.50	1.40
Sorghum	0.56	5.30	2.40
Soybean meal	0.41	6.10	3.20
Vegetable oils	1.59	11.00	3.00
Spent grains	0.38	7.37	0.00
Vegetal and fruit refuse*	0.00	0.00	0.00
Water	0.00	0.00	0.00
Wheat	0.40	2.90	1.10
Wheat bran	0.43	4.80	0.53
Wheat middlings	0.25	2.20	0.60

[1]Obtained from ecoinvent database v3.3 except for those products indicated with *, which were considered to be wasted and have no environmental impact.

4.2. Food safety

Although the use of residual streams as a feeding substrate offer the potential to reduce the environmental impact, they might result into food safety risks. It is therefore required to assess the potential associated food safety issues resulting from the use of residual streams as feed and, if food safety hazards are present, to investigate ways to mitigate them. For some compounds that might pose a safety risk, incorporating BSF larvae in the food chain might result into reduction of the compound (e.g. aflatoxin B1 in Bosch et al., 2017; Purschke et al., 2017; Camenzuli et al., 2018) whereas for others, it might result into accumulation

Table 4
Environmental impact of black soldier fly larvae production in terms of global warming potential (GWP; kg CO_2-eq), energy use (MJ) and land use (m^2) per kg of fresh larvae reared on a resource per legal group.

Group[a]	GWP		Energy use		Land use	
	Average	Range	Average	Range	Average	Range
A (10 values)	1	0–3	17	2–24	5	0–11
B (4 values)	1	0–1	6	2–10	0	0–0
D (1 value)	0	-	1	-	0	-
E (12 values)	0	0–1	2	0–3	0	0–0
Total (27 values)	1	0–3	8	0–24	2	0–11

[a] Groups of insect feeding source options according to legislation in European Union (see Table 1).

Table 5
Comparison between soybean meal and fishmeal and black soldier fly (BSF) larvae per kg protein for global warming potential (GWP; CO_2-eq), energy use (MJ) and land use (m^2).

Parameter	Fishmeal	Soybean meal	BSF[a]		
			Food	Feed	Residual
GWP[b]	2.8	1.1	19	3	6
Energy use[b]	44	9	174	84	26
Land use	0.0	3.4	67	3	0

[a] BSF-Food are larvae reared on products that humans can consume, BSF-Feed are larvae reared on co-products that are generally fed to livestock, and BSF-Residual are larvae reared on products that are not used as food and feed.
[b] Drying is excluded, which, depending on the method, would increase GWP and energy use.

by BSF larvae and pose risks (e.g. cadmium in Diener et al., 2015; van der Fels-Klerx et al., 2016; Purschke et al., 2017).

4.3. Resource conversion efficiency

The characteristics of the organic resources play a pivotal role for this concept as well as how efficiently these can be converted into insect biomass. Next to the amount of larval biomass produced per unit of resource, the larval composition can be greatly influenced by the resource. Crude protein contents of BSF larvae can range considerably with values from 34.9% of DM (Diener et al., 2009) to 57.0% (Dierenfeld and King, 2008), which would impact the nutritional value, the required processing and, ultimately, the economics of production. Our results show that BSF larvae can thrive on a wide range of organic resources, but the DM conversion efficiency is known for less than 25% of the resources studied and N conversion for 17% of the resources. Furthermore, it was noted that test procedures varied considerably (Table 2) and that procedures in some studies were suboptimal to obtain efficient conversion. For example, excessive fungal growth on the beet pulp was suggested to have inhibited larval development and to have caused the observed low DM conversion factor (Tschirner and Simon, 2015). Oonincx et al. (2015b) commented that the drying procedure applied on the three manure types could have been detrimental to their nutritional value and/or the microbiota in the manure. In Tinder et al. (2017) destructive sampling of larvae was performed during the study, which reduced larval development and survival. Furthermore, the latter study reported considerable variation in outcomes between two trials with identical resources, which was potentially due to the use of different incubators and the season in which the study was performed. Considering these issues, one should be cautious in considering the presented efficiencies as representative for the resources tested.

Though the scientific literature describing studies on resource use by BSF larvae is rapidly growing, the studies vary considerable in design. Standardised chemical characterization of the organic resource used, basic rearing methodology, and post-harvest analyses of larvae and residue are crucial to assess the potential of BSF larvae to convert such resources and to improve our understanding of factors important for efficient conversion. Such standardised operating procedures are in place for evaluating ingredients for livestock species. This has resulted in publicly available feeding tables (e.g. Sauvant et al., 2004; CVB, 2011) describing species-specific nutritional values of ingredients, which are instrumental for formulating diets supporting optimal animal performance and use of resources. Researchers are preparing standardised procedures for BSF larvae conversion studies and for reporting of findings (Bosch et al., submitted), which will facilitate comparisons among studies and use of data for future assessments of associated environmental impact for various resources used to produce the larvae.

Both fishmeal and soybean meal are products present in the market since a long time, and their production efficiency has increased in the previous decades, lowering their impacts on the environment. We expect a similar increase in efficiency to evolve in the insect industry. Feed optimization and genetic strain selection could lead to a general improvement of the production efficiency, lowering the resulting environmental impact. At present, we are just starting with understanding the factors that underlie the capacity to efficiently convert residual feeding substrates. It is expected that efficiencies can be increased with the advancement in understanding of how to optimise the interplay between the larvae and residing microbiota in the feeding substrate during rearing and by tailoring BSF larvae strains to specific resources by genetic

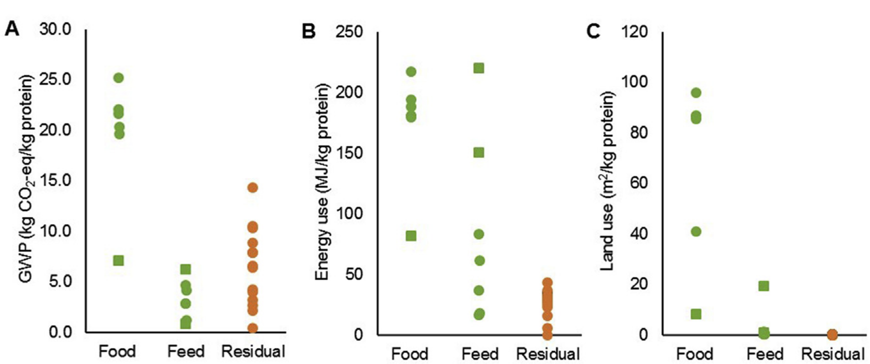

Fig. 2. Environmental impact of black soldier fly larvae production in terms of global warming potential (GWP; panel A), energy use (B) and land use (C) reared on a resource being a food, feed or residual product[1].
[1]Food products are products that humans can consume (n = 6 values); feed products are co-products that are generally fed to livestock (n = 7); and residual products are products that are not used as food and feed (n = 14). Colours refer to the legal status according to the European Union, i.e. allowed in green, not allowed in orange (for details see Table 1). The data points depicted as squares were used as reference resources in studies (see Fig. 1).

selection. With many of the biological and technological concepts being already in place and the short lifecycle of insects, it is possible that improvements can be achieved on the short term with low costs relative to the livestock sector that ultimately lead to a more economic larval production with a lower environmental footprint.

5. Conclusions

The number of studies evaluating the conversion of organic resources by BSF larvae is growing, but vary considerably in design and few actually quantified conversion efficiency. Our results on environmental impact show that resources within the legal groups that are, at the moment, not allowed in EU as animal feed, have in general a lower environmental impact than the ones that are currently allowed. BSF larvae reared on a resource containing residual streams therefore offer potential to replace conventional feed protein sources and, thereby, to lower the environmental impact of food production. More studies evaluating specifically these residual resources as well as the assessments of potential food safety risks are required to relax EU legislation and to bring promising residual streams into the food chain via BSF larvae. BSF larvae reared on a resource that contains food and feed products generally have relatively high environmental impacts. Further developments BSF production technology will lower the environmental impact for these resources as well as making the production more economic and competitive and contributing to reduction of the need for fishmeal and soybean meal as animal feed.

Declaration of interest

None.

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Appendix A. Supplementary data

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References

Alexandratos, N., Bruinsma, J., 2012. World Agriculture towards 2030/2050; the 2012 Revision, Expert Meeting on How to Feed the World in 2050. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 147.

Andriukaitis, V., 2017. Speech at IPIFF Conference "Insects for Food and Feed: Opportunities for Tackling Societal Challenges. https://ec.europa.eu/commission/commissioners/2014-2019/andriukaitis/announcements/speech-ipiff-conference-insects-food-and-feed-opportunities-tackling-societal-challenges-brussels_en. (Accessed 31 July 2018).

Barragan-Fonseca, K.B., Dicke, M., Van Loon, J.J.A., 2017. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review. J. Insect. Food Feed 3, 105–120. https://doi.org/10.3920/JIFF2016.0055.

Barroso, F.G., de Haro, C., Sánchez-Muros, M.J., Venegas, E., Martínez-Sánchez, A., Pérez-Bañón, C., 2014. The potential of various insect species for use as food for fish. Aquaculture 422–423, 193–201. https://doi.org/10.1016/j.aquaculture.2013.12.024.

Baumann, H., Tillman, A.M., 2004. The Hitch Hiker's Guide to LCA. Studentlitteratur, Lund, Sweden.

Bondari, K., Sheppard, D.C., 1981. Soldier fly larvae as feed in commercial fish production. Aquaculture 24, 103–109. https://doi.org/10.1016/0044-8486(81)90047-8.

Bosch, G., Van der Fels-Klerx, H.J., De Rijk, T.C., Oonincx, D.G.A.B., 2017. Aflatoxin B1 tolerance and accumulation in black soldier fly larvae (*Hermetia illucens*) and yellow mealworms (*Tenebrio molitor*). Toxins 9, E185. https://doi.org/10.3390/toxins9060185.

Camenzuli, L., van Dam, R., de Rijk, T., Andriessen, R., van Schelt, J., van der Fels-Klerx, H.J.I., 2018. Tolerance and excretion of the mycotoxins aflatoxin B1, zearalenone, deoxynivalenol, and ochratoxin A by alphitobius diaperinus and hermetia illucens from contaminated substrates. Toxins 10. https://doi.org/10.3390/toxins10020091.

Coenen, P.W.H.G., van Zanten, M.C., Zijlema, P.J., Arets, E.J.M.M., Baas, K., van den Berghe, A.C.W.M., van Huis, E.P., Geilenkirchen, G., Hoen, M.'t, Hoogsteen, M., te Molder, R., Dröge, R., Montfoort, J.A., Peek, C.J., Vonk, J., Dellaert, S., Koch, W.W.R., 2018. Greenhouse Gas Emissions in the Netherlands 1990–2016 National Inventory Report 2018. National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands, p. 406.

CVB, 2011. CVB Veevoedertabel 2011: chemische samenstellingen en nutritionele waarden van voedermiddelen [CVB Feedstuff table 2011: chemical compositions and nutritional values of feedstuffs]. CVB Productschap Diervoeder, Den Haag.

De Marco, M., Martínez, S., Hernandez, F., Madrid, J., Gai, F., Rotolo, L., Belforti, M., Bergero, D., Katz, H., Dabbou, S., Kovitvadhi, A., Zoccarato, I., Gasco, L., Schiavone, A., 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. Anim. Feed Sci. Technol. 209, 211–218. https://doi.org/10.1016/j.anifeedsci.2015.08.006.

Diener, S., Studt Solano, N.M., Roa Gutiérrez, F., Zurbrügg, C., Tockner, K., 2011. Biological treatment of municipal organic waste using black soldier fly larvae. Waste Biomass Valori. 2, 357–363. https://doi.org/10.1007/s12649-011-9079-1.

Diener, S., Zurbrügg, C., Tockner, K., 2009. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. Waste Manag. Res. 27, 603–610.

Diener, S., Zurbrügg, C., Tockner, K., 2015. Bioaccumulation of heavy metals in the black soldier fly, *Hermetia illucens* and effects on its life cycle. J. Insect. Food Feed 1, 261–270. https://doi.org/10.3920/jiff2015.0030.

Dierenfeld, E.S., King, J., 2008. Digestibility and mineral availability of Phoenix worms (*Hermetia illucens*) ingested by mountain chicken frogs (*Leptodactylus fallax*). J. Herpetol. Med. Surg. 18, 100–105. https://doi.org/10.5818/1529-9651.18.3-4.100.

EFSA, 2015. Risk profile related to production and consumption of insects as food and feed. EFSA J 13, 4257. https://doi.org/10.2903/j.efsa.2015.4257.

Finke, M.D., 2013. Complete nutrient content of four species of feeder insects. Zoo Biol. 32, 27–36. https://doi.org/10.1002/zoo.21012.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818. https://doi.org/10.1126/science.1185383.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo De Haes, H.A., De Bruijn, H., Van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Van der Ven, B.L., Weidema, B.P., 2002. Life Cycle Assessment: an Operational Guide to the ISO standards. Centrum Voor Milieukunde. Leiden University, Leiden, the Netherlands. https://doi.org/10.1016/S0195-9255(02)00101-4.

Halloran, A., Hanboonsong, Y., Roos, N., Bruun, S., 2017. Life cycle assessment of cricket farming in north-eastern Thailand. J. Clean. Prod. 156, 83–94. https://doi.org/10.1016/j.jclepro.2017.04.017.

Henry, M., Gasco, L., Piccolo, G., Fountoulaki, E., 2015. Review on the use of insects in the diet of farmed fish: past and future. Anim. Feed Sci. Technol. 203, 1–22. https://doi.org/10.1016/j.anifeedsci.2015.03.001.

IPCC, 2006. Intergovernmental Panel on Climate Change. Guidelines for national greenhouse gas inventories. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Agriculture, Forestry and Other Land Use. IGES, Japan.

Janssen, R.H., Vincken, J.-P., Van den Broek, L.A.M., Fogliano, V., Lakemond, C.M.M., 2017. Nitrogen-to-protein conversion factors for three edible insects: *Tenebrio molitor, Alphitobius diaperinus*, and *Hermetia illucens*. J. Agric. Food Chem. 65, 2275–2278. https://doi.org/10.1021/acs.jafc.7b00471.

Lardé, G., 1990. Recycling of coffee pulp by *Hermetia illucens* (Diptera: Stratiomyidae) larvae. Biol. Wastes 33, 307–310. https://doi.org/10.1016/0269-7483(90)90134-E.

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

Liland, N.S., Biancarosa, I., Araujo, P., Biemans, D., Bruckner, C.G., Waagbø, R., Torstensen, B.E., Lock, E.J., 2017. Modulation of nutrient composition of black soldier fly (*Hermetia illucens*) larvae by feeding seaweed-enriched media. PLoS One 12, e0183188. https://doi.org/10.1371/journal.pone.0183188.

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008.

Mertenat,, A., Diener, S.C.Z., 2019. Black Soldier Fly biowaste treatment – Assessment of global warming potential. Waste Manag 84, 173–181. https://doi.org/10.1016/j.wasman.2018.11.040.

Newton, G.L., Booram, C.V., Barker, R.W., Hale, O.M., 1977. Dried *Hermetia illucens* larvae meal as a supplement for swine. J. Anim. Sci. 44, 395–400.

Oonincx, D.G.A.B., de Boer, I.J.M., 2012. Environmental impact of the production of mealworms as a protein source for humans - a life cycle assessment. PLoS One 7. https://doi.org/10.1371/journal.pone.0051145.

Oonincx, D.G.A.B., van Broekhoven, S., van Huis, A., van Loon, J.J.A., 2015a. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PLoS One 10, e0144601. https://doi.org/10.1371/journal.pone.0144601.

Oonincx, D.G.A.B., van Huis, A., van Loon, J.J.A., 2015b. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. J. Insect. Food Feed 1, 131–139. https://doi.org/10.3920/JIFF2014.0023.

Parra Paz, A.S., Carrejo, N.S., Gómez Rodríguez, C.H., 2015. Effects of larval density and feeding rates on the bioconversion of vegetable waste using black soldier fly larvae *Hermetia illucens* (L.), (Diptera: Stratiomyidae). Waste Biomass Valori. 6, 1059–1065. https://doi.org/10.1007/s12649-015-9418-8.

Pastor, B., Velasquez, Y., Gobbi, P., Rojo, S., 2015. Conversion of organic wastes into fly larval biomass: bottlenecks and challenges. J. Insect. Food Feed 1, 179–193. https://doi.org/10.3920/JIFF2014.0024.

Purschke, B., Scheibelberger, R., Axmann, S., Adler, A., Jäger, H., 2017. Impact of substrate contamination with mycotoxins, heavy metals and pesticides on the growth performance and composition of black soldier fly larvae (Hermetia illucens) for use in the feed and food value chain. Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess. 34, 1410–1420. https://doi.org/10.1080/19440049.2017.1299946.

Rehman, K.U., Cai, M., Xiao, X., Zheng, L., Wang, H., Soomro, A.A., Zhou, Y., Li, W., Yu, Z., Zhang, J., 2017a. Cellulose decomposition and larval biomass production from the co-digestion of dairy manure and chicken manure by mini-livestock (*Hermetia illucens* L.). J. Environ. Manag. 196, 458–465. https://doi.org/10.1016/j.jenvman.2017.03.047.

Rehman, K.U., Rehman, A., Cai, M., Zheng, L., Xiao, X., Somroo, A.A., Wang, H., Li, W., Yu, Z., Zhang, J., 2017b. Conversion of mixtures of dairy manure and soybean curd residue by black soldier fly larvae (*Hermetia illucens* L.). J. Clean. Prod. 154, 366–373. https://doi.org/10.1016/j.jclepro.2017.04.019.

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., Savastano, D., 2017. Environmental impact of food waste bioconversion by insects: application of Life Cycle Assessment to process using *Hermetia illucens*. J. Clean. Prod. 140, 890–905. https://doi.org/10.1016/j.jclepro.2016.06.154.

Sauvant, D., Perez, J.M., Tran, G., 2004. Tables of Composition and Nutritional Value of Feed Materials: Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses and Fish. Wageningen Academic Publishers, Wageningen, The Netherlands.

Smetana, S., Palanisamy, M., Mathys, A., Heinz, V., 2016. Sustainability of insect use for feed and food: life Cycle Assessment perspective. J. Clean. Prod. 137, 741–751. https://doi.org/10.1016/j.jclepro.2016.07.148.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., De Haan, C., 2006. Livestock's long shadow: Environmental issues and options. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Testa, M., Stillo, M., Maffei, G., Andriolo, V., Gardois, P., Zotti, C.M., 2017. Ugly but tasty: a systematic review of possible human and animal health risks related to entomophagy. Crit. Rev. Food Sci. Nutr. 57, 3747–3759. https://doi.org/10.1080/10408398.2016.1162766.

Tinder, A.C., Puckett, R.T., Turner, N.D., Cammack, J.A., Tomberlin, J.K., 2017. Bioconversion of sorghum and cowpea by black soldier fly (*Hermetia illucens* (L.)) larvae for alternative protein production. J. Insect. Food Feed 3, 121–130. https://doi.org/10.3920/JIFF2016.0048.

Tschirner, M., Simon, A., 2015. Influence of different growing substrates and processing on the nutrient composition of black soldier fly larvae destined for animal feed. J. Insect. Food Feed 1, 249–259. https://doi.org/10.3920/JIFF2014.0008.

van Bruggen, C., 2018. Animal Manure and Minerals (2017). In: Dutch: Dierlijke mest en mineralen). Centraal Bureau voor de Statistiek, Den Haag, The Netherlands, p. 42.

van der Fels-Klerx, H.J., Camenzuli, L., Belluco, S., Meijer, N., Ricci, A., 2018. Food safety issues related to uses of insects for feeds and foods. Compr. Rev. Food Sci. Food Saf. 17, 1172–1183. https://doi.org/10.1111/1541-4337.12385.

van der Fels-Klerx, H.J., Camenzuli, L., van der Lee, M.K., Oonincx, D.G.A.B., 2016. Uptake of cadmium, lead and arsenic by *Tenebrio molitor* and *Hermetia illucens* from contaminated substrates. PLoS One 11. https://doi.org/10.1371/journal.pone.0166186.

van Huis, A., 2013. Potential of insects as food and feed in assuring food security. Annu. Rev. Entomol. 58, 563–583. https://doi.org/10.1146/annurev-ento-120811-153704.

van Huis, A., van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P., 2013. Edible Insects: Future Prospects for Food and Feed Security. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

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. CRC Press, Boca Raton, FL, US, pp. 79–124.

van Zanten, H.H.E., Mollenhorst, H., Oonincx, D.G.A.B., Bikker, P., Meerburg, B.G., de Boer, I.J.M., 2015. From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. J. Clean. Prod. 102, 362–369. https://doi.org/10.1016/j.jclepro.2015.04.106.

Varelas, V., Langton, M., 2017. Forest biomass waste as a potential innovative source for rearing edible insects for food and feed – a review. Innov. Food Sci. Emerg. Technol. 41, 193–205. https://doi.org/10.1016/j.ifset.2017.03.007.

Veldkamp, T., Van Duinkerken, G., Van Huis, A., Lakemond, C.M.M., Ottevanger, E., Bosch, G., Boekel, M.A.J.S., 2012. Insects as a Sustainable Feed Ingredient in Pig and Poultry Diets: a Feasibility Study. Wageningen UR Livestock Research, Wageningen UR Livestock Research, Lelystad, the Netherlands, p. 48.

Zheng, L., Li, Q., Zhang, J., Yu, Z., 2012. Double the biodiesel yield: rearing black soldier fly larvae, *Hermetia illucens*, on solid residual fraction of restaurant waste after grease extraction for biodiesel production. Renew. Energy 41, 75–79. https://doi.org/10.1016/j.renene.2011.10.004.