Journal of Cleaner Production 102 (2015) 362–369

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed

Hannah H.E. van Zanten [a, b, *], Herman Mollenhorst [a], Dennis G.A.B. Oonincx [c], Paul Bikker [b], Bastiaan G. Meerburg [b], Imke J.M. de Boer [a]

[a] Animal Production Systems group, Wageningen University, PO Box 338, 6700 AH Wageningen, The Netherlands
[b] Wageningen UR Livestock Research, Wageningen University and Research Centre, PO Box 338, 6700 AH Wageningen, The Netherlands
[c] Laboratory of Entomology, Wageningen University, PO Box 8031, 6700 EH Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form
24 April 2015
Accepted 24 April 2015
Available online 5 May 2015

Keywords:
Insects
House fly larvae
Anaerobic digestion
Environment
Livestock feed
Life cycle assessment

ABSTRACT

The livestock sector is in urgent need for more sustainable feed sources, because of the increased demand for animal-source food and the already high environmental costs associated with it. Recent developments indicate environmental benefits of rearing insects for livestock feed, suggesting that insect-based feed might become an important alternative feed source in the coming years. So far, however, this potential environmental benefit of waste-fed insects is unknown. This study, therefore, explores the environmental impact of using larvae of the common housefly grown on poultry manure and food waste as livestock feed. Data were provided by a laboratory plant in the Netherlands aiming to design an industrial plant for rearing housefly larvae. Production of 1 ton dry matter of larvae meal directly resulted in a global warming potential of 770 kg CO_2 equivalents, an energy use of 9329 MJ and a land use of 32 m^2, caused by use of water, electricity, and feed for flies, eggs and larvae. Production of larvae meal, however, also has indirect environmental consequences. Food waste, for example, was originally used for production of bio-energy. Accounting for these indirect consequences implies, e.g., including the environmental impact of production of energy needed to replace the original bio-energy function of food waste. Assuming, furthermore, that 1 ton of larvae meal replaced 0.5 ton of fishmeal and 0.5 ton of soybean meal, the production of 1 ton larvae meal reduced land use (1713 m^2), but increased energy use (21,342 MJ) and consequently global warming potential (1959 kg CO_2-eq). Results of this study will enhance a transparent societal and political debate about future options and limitations of larvae meal as livestock feed. Results of the indirect environmental impact, however, are situation specific, e.g. in this study food waste was used for anaerobic digestion. In case food waste would have been used for, e.g., composting, the energy use and related emission of greenhouse gases might decrease. Furthermore, the industrial process to acquire housefly larvae meal is still advancing, which also offers potential to reduce energy use and related emissions. Eventually, land scarcity will increase further, whereas opportunities exist to reduce energy use by, e.g., technical innovations or an increased use of solar or wind energy. Larvae meal production, therefore, has potential to reduce the environmental impact of the livestock sector.

1. Introduction

The livestock sector is in urgent need for alternative, more sustainable feed sources, because of the increased demand for animal-source food and the already high environmental costs associated with production of livestock feed. The current livestock sector is responsible for about 15% of the anthropogenic emissions of greenhouse gases (Gerber et al., 2013), mostly related to production and utilization of feed (De Vries and De Boer, 2010). The sector also increasingly competes for scarce resources, such as land,

Abbreviations: FAO, Food and Agricultural Organization; SBM, soybean meal; DM, dry matter; EU, energy use; LU, land use; GWP, global warming potential; LUC, land use change; CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; IPCC, Intergovernmental Panel on Climate Change.

* Corresponding author. Animal Production Systems Group, Wageningen University, PO Box 338, 6700 AH Wageningen, The Netherlands. Tel.: +31 (0)317 483959.

E-mail address: hannah.vanzanten@wur.nl (H.H.E. van Zanten).

http://dx.doi.org/10.1016/j.jclepro.2015.04.106
0959-6526/

water, and fossil energy (Godfray et al., 2010; Steinfeld et al., 2006). Livestock production currently uses about 70% of the agricultural land (Steinfeld et al., 2006), mainly for pasture and production of feed crops. Expansion of the area for livestock production leads to deforestation in the tropics, i.e. 80% of new croplands are replacing forest, resulting in biodiversity loss and increased carbon emissions (Foley et al., 2007, 2011; Gibbs et al., 2010). Without major changes, therefore, the above described environmental concerns will only increase further. One of the major challenges, therefore, is sustainable production of livestock feed.

Recent developments indicate environmental benefits of rearing insects for livestock feed (Sánchez-Muros et al., 2014; Van Huis et al., 2013). Insects have a low feed conversion ratio (kg dry matter feed/kg product) and can be consumed completely, without residual materials as bones or feathers. The nutritional value of insects is high, especially as a protein source for livestock (Veldkamp et al., 2012). Insect-based feed products, therefore, can replace conventional feed ingredients, like fishmeal or soybean meal (SBM), which are associated with a high environmental impact (Van Huis et al., 2013; Veldkamp et al., 2012). The use of insects may reduce the environmental impact of livestock production. In contrast with cultivation of feed crops, production of insects is not necessarily land intensive, especially because insects can turn organic waste streams, such as manure or food waste, into high quality insect-based feed products (Sánchez-Muros et al., 2014; Van Huis et al., 2013; Veldkamp et al., 2012). In Western countries large amounts of manure are produced and, according to the FAO one third of the produced food is never consumed (Gustavsson et al., 2011). Already in the 1970s, it was proven that housefly larvae (*Musca domestica* L.) can be used for biodegradation of chicken manure (Calvert et al., 1970) and that larvae can grow on municipal organic waste (Ocio et al., 1979). Moreover, feeding houseflies reared on manure and food waste to livestock will reduce the competition for land between food and feed, because they can replace other feed ingredients that are directly edible by humans. As an example, about 70% of the cereal grains used in developed countries is fed to livestock (Eisler et al., 2014). Due to a rather inefficient feed conversion ratio of livestock – for chicken 1.6, for pigs 2.5 and cattle 5.1 (Šebek and Temme, 2009) – more people could be supported from the same amount of land if they did not consume meat from livestock fed with cereals (Godfray et al., 2010). Feeding waste-fed insects to livestock, therefore, might be an effective strategy as inedible waste streams for livestock and humans can be used to produce high quality food products, such as meat, milk, and eggs.

Altogether, waste-fed insects seem to be a promising feed source for livestock, and therefore can be part of the solution to fulfil the growing demand for animal-source food, within the carrying capacity of the earth.

To our knowledge, however, no study has been published that quantified the reduction of the environmental impact of including waste-fed insects in livestock feed. Only one peer-reviewed study analyzed the environmental impact of insects, in this case mealworms (Oonincx and De Boer, 2012). This study, however, focussed on production of mealworms for human consumption, and showed that the production of one kg of edible protein from mealworms resulted in a lower land use (LU), but a higher energy use (EU), and consequently also a higher global warming potential (GWP) than production of one kg of edible protein from livestock (Oonincx and De Boer, 2012). It is questionable, therefore, whether or not the production of waste-fed insects will result in environmental benefits.

The aim of this study, therefore, is to explore whether the environmental impact of livestock production can be reduced by the use of larvae of the common housefly grown on organic waste streams as livestock feed.

2. Materials and methods

Life cycle assessment (LCA) was used to assess the environmental impact of larvae meal production. LCA is an internationally accepted and standardized holistic method (ISO 14044, 2006; ISO 14040, 2006) to evaluate the environmental impact during the entire production chain (Bauman and Tillman, 2004; Guinée et al., 2002). LCA includes four phases: 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 livestock production when larvae of the common housefly grown on organic waste streams are used as livestock feed, including also the environmental consequences to replace the original application of this waste. The functional unit was 1 ton larvae meal on dry matter (DM) basis.

Inventory analysis. Data related to the required inputs and outputs to produce 1 ton of larvae meal were obtained from a business model. This model was based on experimental studies and developed by four companies in the Netherlands (Jagran, an insect rearing company, supported by AEB and SITA, two waste processing companies, and Denkavit, an animal nutrition company).

Impact assessment. To assess the environmental impact, two types of impacts were considered: use of resources, such as land or fossil energy, and emission of pollutants, such as carbon dioxide or nitrous oxide (Guinée et al., 2002). The following impact categories were assessed: climate change, generally expressed as GWP, energy use and land use. Climate change and LU were chosen because the livestock sector contributes significantly to both emission of greenhouse gases and LU worldwide (Steinfeld et al., 2006). EU was included also because Oonincx and De Boer (2012) showed that rearing insects is energy-demanding, and because fossil energy is a scarce resource. The following greenhouse gases were considered: CO_2, CH_4, and N_2O. These greenhouse gases were summed based on their equivalence factors in terms of CO_2-eq (100 years' time horizon): i.e. 1 for CO_2, 25 for CH_4, and 298 for N_2O (Forster et al., 2007), and expressed per ton larvae meal (DM). LU was expressed in m^2 per ton larvae meal (DM) per year, whereas energy use (EU) was expressed in MJ per ton larvae meal (DM). Data related to emissions and resources were mainly obtained from databases and literature 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). Economic allocation is most commonly used in LCA studies of livestock products (De Vries and De Boer, 2010).

The direct and indirect environmental impacts related to the production of 1 ton of larvae meal were assessed (Fig. 1). Direct environmental impacts resulted from the use of resources and emissions of pollutants related to the housefly farm, such as use of water, electricity or feed, and emissions of greenhouse gases from waste during insect rearing. The indirect environmental impacts related to changes in use of farm inputs or outputs produced. Food waste, for example, used for insect rearing, might have been used originally to produce biogas. To evaluate the impact of using food waste for insect rearing, therefore, the environmental impacts of, for example, production of fossil energy needed to replace the original bio-energy function of food waste was included also. Below the direct environmental impact and indirect environmental impact are explained in more detail.

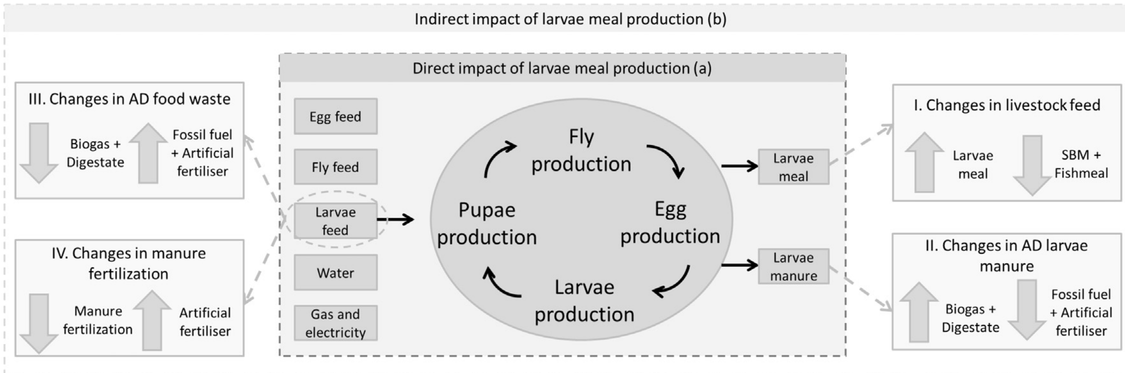

Fig. 1. Production chain of larvae meal. Box (a) shows the life cycle of housefly larvae with the related input products that are required to maintain a certain output of larvae meal and larvae manure. Box (b) shows the four indirect environmental changes that will occur when larvae meal is used as livestock feed: changes in livestock feed, changes in anaerobic digestion (AD) and changes in manure fertilization.

2.1. *Direct environmental impact of larvae meal*

Data were needed on all farm inputs and outputs related to the production of 1 ton larvae meal (DM) to assess the direct environmental impacts of housefly rearing. These data were based on a business model aimed at producing 65 ton of fresh larvae per day, resulting in 20 ton of larvae meal with a DM content of 88%. The production cycle started with housefly pupae, which eclosed within 2 days. Feed for the flies consisted of sugar, milk powder and egg powder. Flies were kept at a temperature of 25 °C. Female flies start to lay eggs after 7 days in an oviposition substrate, consisting of milk powder, yeast, fibre, vegetable oil and premix (vitamins and minerals). After oviposition, the mixture of eggs with substrate was added to a larvae-substrate (feed for the larvae). The larvae-substrate consisted of food waste, laying hen manure and premix. Larvae were kept at a temperature of 27 °C and were fully grown after 5 days. Per 4 kg of larvae-substrate, 1 kg of fresh larvae was produced. Harvesting of the larvae was performed by shutting off the ventilation, which forces the larvae to migrate to the surface of the substrate because of a drop in oxygen level. The harvested larvae were dried, which is generally required before the larvae can be included into livestock feed. As the larvae production was situated next to a waste incineration facility, the remaining heat of this facility was aimed for drying. After approximately 35 days the fly colony dies. Therefore, part of the larvae is kept to evolve into pupae to maintain the production chain.

A summary of the environmental impacts of input and output data required to maintain the production of larvae meal is provided in Table 1 and further explained below.

The environmental impacts (i.e. GWP, EU and LU) related to the production of feed for the flies, and egg substrate were based on Vellinga et al. (2013) and Mosnier et al. (2011), and exact composition data, which are not disclosed for industrial competitive protection. Environmental impacts from production of various feed ingredients included impacts from cultivation (e.g. fertilizers, pesticides, machinery, energy, emissions related to direct and indirect N_2O and CO_2 emissions from liming and urea fertilization), impacts from drying and processing, and impacts from transport up to the farm gate.

The environmental impacts (i.e. GWP, EU and LU) related production and use of tap water, natural gas, and electricity were based on Eco-invent (EcoinventCentre, 2007). Electricity was assumed to be substituted with marginal Dutch electricity, i.e. 28% coal-based, 67% natural gas-based, and 5% wind-based electricity (De Vries et al., 2012a).

Emissions of GHG related to the substrate for the larvae were based on IPCC (IPCC, 2006). According to IPCC, emissions of CH_4 from organic waste occur only after several months. As food waste was used during the larvae production process for 4 days only, it was assumed that emissions from organic waste were negligible. During the handling and storage of laying hen manure, CH_4 and direct and indirect N_2O were emitted. As there were no specific data available about the use of manure for insect rearing, it was assumed that emissions for using manure were equal to emissions emitted on a laying hen farm. To estimate CH_4 emission, a tier 2 approach was used based on country specific data (Coenen et al., 2013) and IPCC default values (IPCC, 2006) (an organic matter content of 0.35 kg per kg manure, maximum CH_4 producing potential of 0.34 m^3 CH_4 per kg organic matter and a methane conversion factor of 0.015). To estimate direct and indirect N_2O emissions, a tier 2 approach was used based on country specific data of Coenen et al., 2013 (direct: 0.8 kg N excretion per laying hen per year, 18.9 kg manure per laying hen per year and a default emission factor of 0.01) (indirect: volatilization 40% and an

Table 1
Input data and related global warming potential (GWP), energy use (EU) and land use (LU) data with references for the direct environmental impact of producing 1 ton dry matter larvae meal.

Ingredients	Unit	Amount(/ton DM)	GWP (g CO_2-eq)	EU (MJ)	LU (m^2)	References
Feed flies	kg	1	3808	12.2	1.34	Vellinga et al., 2013
Substrate eggs	kg	17	1351	3.9	0.34	Vellinga et al., 2013
Food waste	kg	11,079	11	0.2	0.00	Coenen et al., 2013; IPCC, 2006
Manure	kg	3693	42	0.2	0.00	EcoinventCentre, 2007; IPCC, 2006
Premix	kg	57	1362	3.9	0.34	EcoinventCentre, 2007; IPCC, 2006; Mosnier et al., 2011
Water	kg	10,309	0	0.0	0.00	EcoinventCentre, 2007
Electricity	kWh	378	753	11.8	0.01	EcoinventCentre, 2007
Gas	kWh	183	586	11.2	0.00	EcoinventCentre, 2007

emission factor of 0.01). The GWP, EU and LU for transportation of food waste and manure over an average of 65 km per day were included, based on Ecoinvent (EcoinventCentre, 2007).

2.2. Indirect environmental impact of larvae meal production

Three major indirect changes were considered. *I) Changes related to a decreased availability of food waste for anaerobic digestion*. Originally, food waste is used for anaerobic digestion in the Netherlands. As the amount of food waste is restricted by the amount of food spilled by humans, using food waste for larvae production decreases its availability for anaerobic digestion. The decreased production of electricity, heat and digestate, therefore, was assumed to be substituted with fossil fuels and synthetic fertilizer. *II) Changes related to manure fertilization.* Laying hen manure used to grow insects was assumed to be used to fertilize crop production in Germany. As the production of laying hen manure is restricted by the demand for eggs, its availability for application on croplands in Germany decreased. Consequentially, laying hen manure was assumed to be substituted with synthetic fertilizer. *III) Changes related to an increased availability of larvae manure for anaerobic digestion*. Larvae manure produced was assumed to be used originally for anaerobic digestion, producing electricity, heat, and digestate. Electricity and heat were assumed to replace fossil fuels. Digestate was assumed to replace synthetic fertilizer. As digestate contains residues of laying hen manure it should be labelled as manure according to Dutch regulation. Due to a manure surplus in the Netherlands, digestate was assumed to be transported to Germany, and used to fertilize crop production.

The method and related data to the above-described indirect changes in anaerobic digestion and manure fertilization are described below.

2.2.1. Environmental impact related to changes in anaerobic digestion

For the anaerobic digestion of food waste and larvae manure a large scale digestion plant was considered. The biogas produced was used in a combined heat and power unit for the production of electricity and heat. Digestion required 110 MJ of electricity per ton and 65 MJ heat per ton based on 10% DM content (Berglund and Börjesson, 2006). Electricity was taken from the grid, whereas heat originated from the combined heat and power unit. Methane losses were 1% of produced CH_4 (Møller et al., 2009; Zwart et al., 2006). The energy efficiency of the heat and power unit was 70%, the electric efficiency 35% (Zwart et al., 2006). The utilization of surplus heat from anaerobic digestion, i.e. the surplus heat that remains after using the required heat for the process, was not included, as heat offset possibilities are limited in the Netherlands (Dumont, 2010). The digestate that is transported and applied to the field as fertilizer, was assumed to substitute marginal mineral N, P, and K fertilizer. Marginal production of mineral fertilizer was assumed to be calcium ammonium nitrate for N, triple superphosphate for P_2O_5, and potassium chloride for K_2O (De Vries et al., 2012a).

Per ton larvae manure (DM) 15 GJ was produced (Table 2). N, P and K values and the methane production potential of larvae manure were provided by Jagran. Jagran performed two analyses of the methane production potential of larvae manure. The first analysis of the larvae manure was based on a sample in which the larvae grew only on food waste and the second analysis was based on a sample in which the larvae grew only on laying hen manure. Results of both analyses were used based on their ratio in the diet (25% manure and 75% food waste). Per ton food waste (DM) 18 GJ could be produced. No analysis was performed on the methane production potential and N, P and K values of food waste. It was therefore, assumed that values for food waste were similar to larvae manure based on a substrate of food waste, when compensated for the difference in DM content. Both food waste and larvae manure were transported to the digestion plant and the digestate to agricultural fields. It was assumed that digestate of food waste was applied on Dutch agricultural fields and digestate of larvae manure on German croplands, as it contains laying hen manure and therefore is not allowed on Dutch fields, resulting in a difference in transport of 370 km. The environmental impact values related to the production of electricity, and N, P, and K fertilizers and transport per lorry were based on Eco-invent (EcoinventCentre, 2007) (Table 3).

2.2.2. Environmental impact related to changes in manure fertilization

Laying hen manure was transported to Germany (435 km assumed) and used as fertilizer replacing artificial fertilizer. Laying hen manure contains 3.57% N, 2.89% P and 2.03% K (Den Boer et al., 2012).

2.3. Comparison of environmental impact of larvae meal with SBM and fish meal

To determine the potential environmental benefit of using larvae meal as livestock feed ingredient, all above described indirect environmental impacts were added to the direct environmental impacts of production of 1 ton larvae meal (DM). Subsequently, the environmental impact of larvae meal was compared with other protein rich feed ingredients, namely SBM and fishmeal. One ton of larvae meal was assumed to replace 0.5 ton of fishmeal and 0.5 ton of SBM on a DM basis. The DM content of larvae meal is 88.0% (based on analysis of the laboratory plant), of fishmeal 92.7% and of SBM 87.5% (CVB, 2010). Table 3 shows the GWP, EU and LU for fishmeal and SBM. For SBM emissions related to LUC were assessed as well, because the production of SBM is related to deforestation which is an important source of GHG emissions (Macedo et al., 2012; Prudêncio da Silva et al., 2010; Van Middelaar et al., 2013). LUC emissions for SBM were 0.47 kg CO_2-eq per m^2 per year, assuming an amortation period of 20 years (De Vries et al., 2012b). Emissions were quantified by considering CO_2 emissions of converting, for example, forest or grassland to cropland, accounting for size and location of converted land and the types of land that were converted (biome types) (Tonini et al., 2012). It was assumed that 20% of the increased soybean demand came from increased yields, whereas 80% was met by expansion of land in Brazil (Kløverpris, 2008; Laborde, 2011) of which 23% rainforest and 77% savannah in the Cerrado region (Prudêncio da Silva et al., 2010). For larvae meal and fishmeal it was assumed

Table 2
Input data anaerobic digestion per ton of organic matter on dry matter basis.

Type	DM	Biogas (nm^3/ton)	CH_4 in biogas (%)	Energy (GJ/ton DM)	N (%)	P (%)	K (%)
Larvae manure: food waste	38	260	65	17	3.28	0.76	0.98
Larvae manure: laying hen manure	30	103	56	8	2.86	3.32	2.99
Food waste	32	218	65	18	2.76	0.64	0.50

Table 3
Global warming potential (GWP), energy use (EU) and land use (LU) data with references for the indirect environmental impact of producing 1 ton dry matter larvae meal.

Ingredients	Unit (/ton DM)	GWP (g CO_2-eq)	EU (MJ)	LU (m^2)	References
Soybean meal	kg DM	710	6.89	3.543	Vellinga et al., 2013
Soybean meal incl LUC	kg DM	2375	6.89	3.543	De Vries et al., 2012b
Fishmeal	kg DM	1636	23.45	0.015	Vellinga et al., 2013
Electricity	kWh	753	11.80	0.006	EcoinventCentre, 2007
N	kg	8543	55.35	0.095	EcoinventCentre, 2007
P_2O_5	kg	2014	25.96	0.087	EcoinventCentre, 2007
K_2O	kg	495	8.06	0.051	EcoinventCentre, 2007
Lorry EURO 4 16–32 ton	Tkm	164	2.57	0.003	EcoinventCentre, 2007

that LUC emissions were negligible, because land use during production is small.

2.4. Sensitivity analysis

Inventory data and data related to emission of GHGs, EU and LU contain uncertainties. A sensitivity analysis was performed in Excel to assess which parameters contained high uncertainty and, therefore, have a high impact on the outcome of the study. Inventory data regarding, for example, the amount of electricity or water used, were changed one by one by ±10%. Moreover, the environmental impact (GWP, EU and LU) related to production of these products was also changed by ±10%. This range of ±10% is more often applied in LCA studies of livestock products, such as in Van Middelaar et al. (2013).

3. Results

First the results of the direct environmental impacts are shown, followed by the results of the indirect environmental impacts. Then a comparison of larvae meal with SBM and fish meal is made, and lastly results of the sensitivity analysis are presented.

3.1. Direct environmental impact of production of larvae meal

Producing larvae meal resulted in a GWP of 770 kg CO_2-eq, an EU of 9329 MJ and an LU of 32 m^2 per ton DM larvae meal (Table 4). The largest part of the GWP was caused by feed for the larvae (44%), whereas an additional 37% resulted from the use of electricity and 14% form the use of gas. Electricity and gas use, however, explained the majority of the EU (70%), whereas production of vitamins and minerals in larvae feed explained the majority of the LU. Note that gas for drying the larvae, which is currently assumed to be necessary before it can be used as livestock feed due to food safety issues, was not included as the remaining heat from a waste incineration facility was used. However, when no residual heat could have been used, one should count for an additional 1247 kg CO_2-eq, 23,949 MJ and 1 m^2 per ton larvae meal (DM). Therefore, gas for drying will have a large impact on EU and consequently on the GWP.

Table 4
Global warming potential (GWP), energy use (EU) and land use (LU) of the production of 1 ton of larvae meal dry matter.

Processes	GWP (kg CO_2-eq)	EU (MJ)	LU (m^2)
Egg production	26	84	7
Egg substrate	23	67	6
Feed flies	2	7	1
Water	1	11	0
Larvae production	353	2733	23
Feed larvae	350	2686	22
Water	3	46	0
Electricity use	284	4458	2
Egg production	21	322	0
Larvae production	164	2575	1
Processing larvae	41	644	0
Lightening building	38	595	0
Working places	21	322	0
Gas for heating	107	2054	0
Total larvae meal	770	9329	32

3.2. Indirect environmental impacts related to changes in farm inputs and outputs

3.2.1. Impacts related to changes in anaerobic digestion of food waste

The increased use of fossil fuels, due to the reduced anaerobic digestion of food waste, increased GWP with 3954 kg CO_2-eq, EU with 62,001 MJ and LU with 32 m^2 per ton larvae meal (DM), whereas the increased use of synthetic fertilizer increased GWP with 895 kg CO_2-eq, EU with 6230 MJ and LU with 13 m^2 per ton DM of larvae meal (Fig. 2).

3.2.2. Impacts related to changes in anaerobic digestion of larvae manure

The decreased use of fossil fuels, due to the increased use of anaerobic digestion of larvae manure, reduced GWP with 3277 kg CO_2-eq, EU with 50,916 MJ and LU with 27 m^2 per ton DM larvae meal (Fig. 2). The decreased use of synthetic fertilizer reduced GWP with 355 kg CO_2-eq, and LU with 5 m^2, but increased EU with 2825 MJ per ton larvae meal (DM), due to transport of larvae manure to Germany (Fig. 2).

3.2.3. Impacts related to changes in manure fertilization

The increased use of synthetic fertilizer, due to the reduced use of manure fertilization, increased GWP with 1146 kg CO_2-eq, EU with 7045 MJ and LU with 22 m^2 per ton DM of larvae meal (Fig. 2).

3.3. Comparison of environmental impact of larvae meal with SBM and fish meal

To determine the potential environmental benefit of larvae meal, the direct environmental impact was added to the indirect environmental impacts of producing 1 ton larvae meal (DM). Production of 1 ton larvae meal (DM) resulted in a GWP of 3132 CO_2-eq, an EU of 36,513 MJ and an LU of 66 m^2. Subsequently, the environmental impact of 1 ton larvae meal was compared with fishmeal and SBM. Using larvae meal instead of SBM and fishmeal resulted in an increased GWP of 1959 kg CO_2-eq (i.e. excluding LUC) or 1364 kg CO_2-eq (i.e. including LUC), EU with 21,342 MJ and LU decreased with 1713 m^2 per ton larvae meal (DM).

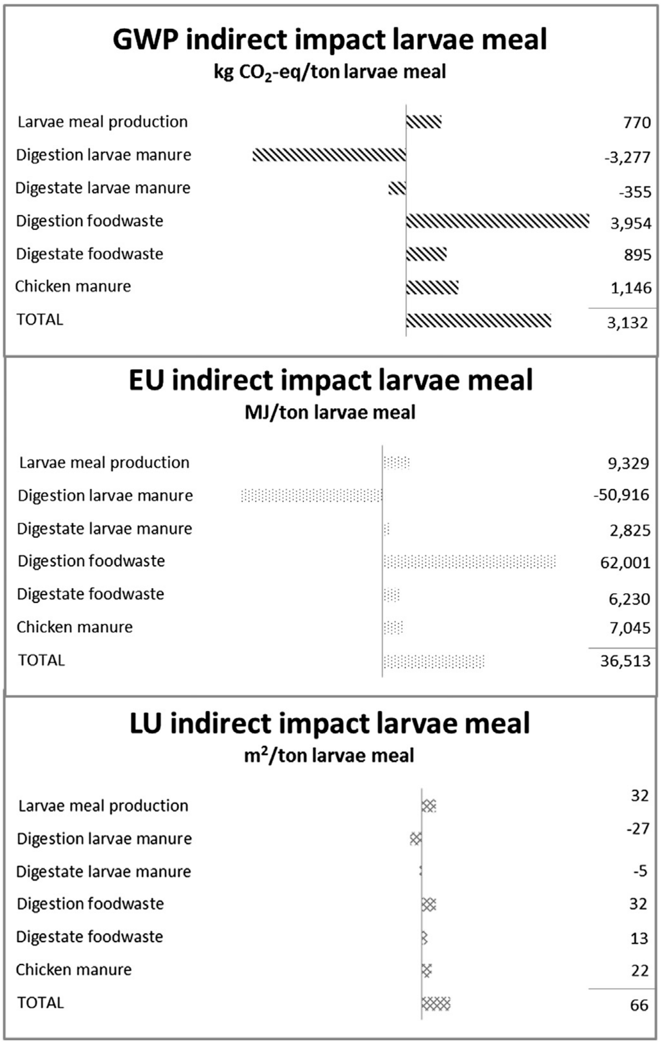

Fig. 2. Indirect environmental impact of larvae meal production. Global warming potential (GWP), energy use (EU) and land use (LU) per kg of dry matter larvae meal for indirect changes of producing larvae meal. By summing up the environmental changes the total indirect environmental impact of larvae meal is obtained.

3.4. *Sensitivity analysis*

Results of the sensitivity analyses showed that the direct GWP was merely determined by energy use (gas and electricity use) and feed for larvae (Table 5), whereas EU was merely determined by electricity use of larvae production, followed by gas use for the total building. LU was mostly influenced by the land used for producing the feed of the larvae.

The indirect GWP and EU however, were merely determined by changes in anaerobic digestion (Table 6). This sensitivity for the process of anaerobic digestion has two causes. First, EU and GWP outcomes highly depend on the methane production potential influencing the amount of energy assumed to be produced by anaerobic digestion. Second, EU and GWP highly depend on the electricity factor used for greenhouse gas emissions, which was merely determined by the mixer of electricity sources (in this cased based on the Dutch situation). LU was mostly influenced by the land used for the production of SBM, and LU outcomes, therefore, were sensitive to changes in the relative replacement of SBM and fishmeal by larvae meal.

Table 5
Sensitivity analysis of direct impact of larvae meal production. Consequences of 10% change in emission factors on global warming potential GWP, energy use (EU) and land use LU of larvae meal per ton larvae meal.

Direct changes	GWP (kg CO_2-eq)	EU (MJ)	LU (m^2)
Larvae meal (total)	770	9329	32
Egg production	3	8	1
Egg substrate	2	7	1
Feed flies	0	1	0
Water	0	1	0
Larvae production	35	273	2
Feed larvae	35	269	2
Water	0	5	0
Electricity use	28	446	0
Egg production	2	32	0
Larvae production	16	257	0
Processing larvae	4	64	0
Lightening building	4	60	0
Working places	2	32	0
Gas for heating	11	205	0

Table 6
Sensitivity analysis of indirect impact of larvae meal production. Consequences of 10% change in impact factors and inventory data on global warming potential (GWP), energy use (EU) and land use (LU) of 1 ton larvae meal dry matter.

Indirect changes	GWP (kg CO_2-eq)	EU (MJ)	LU (m^2)
Larvae meal production (incl. indirect change)	1959	21,342	−1713
Livestock feed			
Impact factor larvae meal	77	933	3
Impact factor fishmeal	81	345	1
Impact factor soybean meal	35	1173	177
Ratio fishmeal and soybean meal	92	1656	353
Anaerobic digestion larvae manure			
Methane production potential	374	5801	3
Impact factor electricity	325	5092	3
EF N, P, K	100	726	2
% N, P, K	100	726	2
Anaerobic digestion food waste			
Methane production potential	457	7152	4
Impact factor electricity	407	6385	3
Impact factor N, P, K	89	623	1
% N, P, K	89	623	1
Laying hen manure			
% N, P, K	138	1067	2

4. Discussion

Results of the sensitivity analysis showed that the following four input data are highly sensitive: electricity and gas use, emissions related to the feed of the larvae, replacement of livestock feed and the methane production potential. Those parameters are below discussed in more detail.

Electricity and gas use were the main contributors to EU and the GWP during the production of larvae meal. A relative high electricity use and gas use for insect rearing were found earlier for mealworm production (Oonincx and De Boer, 2012). Production of one kg of mealworm (DM) used 15.8 MJ of electricity and 26.0 MJ of gas. The higher energy use for production of mealworms was caused by a longer production cycle of mealworms (10 weeks instead of 5 days). Production of mealworms and housefly larvae use high amounts of gas due to the required ambient temperature of the insects. One should, however, take into account that the required energy use was an estimation of the laboratory plant. The industrial process to acquire housefly larvae meal is still advancing, which offers potential to further reduce energy use. Taelman et al. (2013) showed, for example, that up-scaling production of algae as feed for aquaculture reduced the carbon footprint with a factor 20. It is likely, therefore, that further up-scaling of production of larvae meal will further reduce energy use and related GHG emissions.

Emissions of GHG related to larvae-feed contributed most to GWP. Calculations of the larvae feed were based on IPCC guidelines for manure and composting of food waste. It was assumed in this study that emissions of food waste were negligible. Despite food waste is used by larvae for 4 days only, emissions of GHG could have occurred because the circumstances for composting were favourable (i.e. high temperatures and constant ploughing by the larvae). Furthermore, IPCC calculations for manure were based on emissions related to the complete laying hen sector and not only for the storage of manure and, therefore, possibly resulting in an overestimation. To minimize the uncertainty of the environmental impact of larvae meal experimental studies on the emissions related to use of larvae feed are required.

The changes in livestock feed were based on the assumption that larvae meal is used to replace fishmeal and SBM. Although larvae meal, fishmeal and SBM are all protein rich, their nutritional value, i.e. content of amino acids and crude fat, differs. Table 7 shows the nutrient content of larvae meal (based on analysis of the laboratory plant), fishmeal and SBM (CVB, 2010). The nutrient content of larvae meal was based on two samples only, but results are confirmed by a literature review (Veldkamp et al., 2012), showing similar outcomes: larvae contain 43–68% protein and 4–32% fat on a DM basis. Replacing fishmeal and SBM by larvae meal on a DM basis will have an impact on the nutritional composition of the diets such as crude protein or amino acids and net energy. Since the nutritional requirements should be met to maintain the growth performance of the animal, the diet composition will change. It is, therefore, expected that including larvae meal in livestock diets will not only reduce the content of fishmeal and/or SBM, but will affect the complete diet composition. Future research, therefore, should include changes in diet composition and changes on feed intake and growth of the animals. However, until now the nutritional value of larvae meal is highly uncertain. In vivo animal studies are required to determine the palatability, digestibility and other relevant characteristics of larvae meal before a reliable comparison with other feed ingredients can be made.

Assumed values of the methane production potential highly influenced the computation of the amount of energy produced from anaerobic digestion. The methane production potential used in this study, i.e. 15 GJ per ton larvae manure (DM) and 18 GJ per ton food waste (DM), were within the range of values found in other studies: 12 GJ per ton DM of municipal organic waste (Berglund and Börjesson, 2006) and 18 GJ per ton DM of vegetable food waste (Bernstad and la Cour Jansen, 2012). Nevertheless, the difference between the methane production potential of food waste and larvae manure remains uncertain. To minimize the uncertainty of the environmental impact of larvae meal more experimental studies in this direction are required.

Table 7
Nutrient content (%) of larvae meal (based on data of the laboratory plant), fishmeal and soybean meal (SBM) (CVB, 2010).

	Larvae meal	Fishmeal	SBM
Dry matter	88.0	92.7	87.5
Crude protein	47.9	56.7	46.0
Fat	24.2	15.8	18.4
Lysine	32.6	43.1	28.5
Methionine	11.3	15.9	6.4

Although data are based on a Dutch case study (Jagran), the results are valuable for livestock systems across the globe. A global interpretation of current results, however, requires consideration of some site-specific aspects. First, a large part of the direct environmental impact is caused by energy use. Situating the production in a warmer climate than the Netherlands will lower gas requirements and, therefore, lower the GWP and EU. Second, results showed that it is essential to minimize gas use for drying to reduce the GWP and EU. Therefore, larvae production should be situated near, for example, a waste incineration facility, which enables to use its remaining heat for drying. Third, this study shows that the environmental impact of using larvae meal as livestock feed also depends on the current application of the food waste. Using food waste and laying hen manure as feed for larvae in this case study resulted in an increased GWP and EU but a decreased LU compared with the current situation, in which food waste was used for anaerobic digestion and laying hen manure for fertilization. In case food waste is used for composting or does not have a function yet, environmental benefits related to larvae meal will increase. The same applies for the application of the larvae manure. Finding the optimal application for larvae manure is essential to reduce the environmental impact. Finally, some challenges need to be addressed in Europe before large scale larvae production can start. Legislation, health concerns and a high cost price are important issues (Van Huis et al., 2013; Veldkamp et al., 2012). Until now, it is not allowed to include larvae fed on waste streams in livestock feed in the Netherlands. However, in other parts of the world this is less strictly regulated.

The discussion points mentioned in this section provide building blocks to minimize the environmental impact of larvae production. Incorporating the results of this study within designing plans of large scale larvae production provide opportunities to lower GWP and EU while a low LU is maintained.

5. Conclusion

This study is the first study that explores the environmental impact of using larvae meal as livestock feed. Larvae meal can be a promising protein source for the livestock sector that can alleviate future shortages of protein sources in livestock feed. Results of this study will enhance a transparent societal and political debate about future options and limitations of larvae meal as livestock feed.

Production of 1 ton of dry matter larvae meal directly resulted in a global warming potential of 770 kg CO_2-eq, energy use of 9329 MJ and land use of 32 m^2. Energy use is the main contributor to the direct environmental impact of larvae meal production. The industrial process to acquire larvae meal, however, is still advancing which has potential to increase its energy efficiency. Future development of larvae rearing should, therefore, focus on energy saving to ensure the environmentally sustainability of larvae meal as livestock feed.

Production of larvae meal, however, also has indirect environmental consequences, i.e. environmental impacts related to changes in use of farm inputs or outputs produced. Adding the indirect environmental changes to the direct impact resulted in a GWP of 3132 CO_2-eq, an EU of 36,513 MJ and an LU of 66 m^2. Overall, using 1 ton of larvae meal compared with using 0.5 ton of fishmeal and 0.5 ton of SBM on a DM basis resulted in an increased GWP of 1959 kg CO_2-eq (i.e. excluding LUC) or 1364 kg CO_2-eq (i.e.

including LUC), EU of 21,342 MJ and LU decreased with 1713 m^2. Results of the indirect environmental impact, however, are situation specific, e.g. in this study food waste was used for anaerobic digestion. In case food waste would have been used for, e.g., composting, the energy use and related emission of greenhouse gases might decrease. Furthermore, the industrial process to acquire housefly larvae meal is still advancing, which also offers potential to reduce the energy use and related emissions. Nevertheless, at this moment using larvae meal results in a trade-off between decreased land use and increased global warming potential and energy use. Eventually, however, land scarcity will increase further, whereas opportunities exist to reduce energy use by, e.g., technical innovations or an increased use of solar or wind energy. Larvae meal production, therefore, has potential to reduce the environmental impact of the livestock sector.

Acknowledgements

The authors kindly acknowledge Jagran, AEB, SITA and Denkavit for providing company data and insight in their production system. Furthermore, the authors want to thank Wageningen UR Livestock Research for funding this research and Freija van Holsteijn for her help.

References

Bauman, H., Tillman, A.M., 2004. The Hitchhiker's Guide to LCA. Chalmers University of Technology, Götenborg, Sweden.

Berglund, M., Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 30, 254–266.

Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – current status and potential improvements. Waste Manag. 32, 2439–2455.

Calvert, C.C., Morgan, N.O., Martin, R.D., 1970. House fly larvae: biodegradation of hen excreta to useful products. Poult. Sci. 49, 588–589.

Coenen, P.W.H.G., Van der Maas, C.W.M., Zijlema, P.J., Arets, E.J.M.M., Baas, K., Van den Berghe, A.C.W.M., Te Biesebeek, J.D., Brandt, A.T., Geilenkirchen, G., Van der Hoek, K.W., Te Molder, R., Dröge, R., Montfoort, J.A., Peek, C.J., Vonk, J., 2013. Greenhouse Gas Emissions in the Netherlands 1990–2011. National Inventory Report 2013. National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

CVB, 2010. Tabellenboek Veevoeding. CVB-reeks nr. 49. Productschap Diervoeder, Centraal Veevoederbureau, Den Haag, the Netherlands.

De Vries, J.W., Groenestein, C.M., De Boer, I.J.M., 2012a. Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. J. Environ. Manag. 102, 173–183.

De Vries, J.W., Vinken, T.M.W.J., Hamelin, L., De Boer, I.J.M., 2012b. Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy – a life cycle perspective. Bioresour. Technol. 125, 239–248.

De Vries, M., De Boer, I.J.M., 2010. Comparing environmental impacts for livestock products: a review of life cycle assessments. Livest. Sci. 128, 1–11.

Den Boer, D.J., Reijneveld, J.A., Schröder, J.J., Van Middelkoop, J.C., 2012. Manure Composition. Wageningen UR, Lelystad, the Netherlands.

Dumont, M., 2010. Green gas. In: Symposium industriële vergisting. NL Agency, the Hague, the Netherlands.

EcoinventCentre, 2007. Ecoinvent Data v2.0 Final Reports Econinvent 2007. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Eisler, M.C., Lee, M.R.F., Tarlton, J.F., Martin, G.B., Beddington, J., Dungait, J.A.J., Greathead, H., Liu, J., Mathew, S., Miller, H., Misselbrook, T., Murray, P., Vinod, V.K., Van Saun, R., Winter, M., 2014. Steps to sustainable livestock. Nature 507, 32–34.

Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P., 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Front. Ecol. Environ. 5, 25–32.

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., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: the Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change through Livestock – a Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc. Natl. Acad. Sci. 107, 16732–16737.

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.

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.

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste. Food and Agriculture Organization, Rome, Italy.

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, vol. 4. IGES, Japan.

ISO 14040, 2006. Environmental Management – Life Cycle Assessment: Principles and Framework. European Committee for Standardization (CEN), Brussels, Belgium.

ISO 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. European Committee for Standardization (CEN), Brussels, Belgium.

Kløverpris, J.H., 2008. Consequential Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption. Technical University of Denmark, Copenhagen, Denmark.

Laborde, D., 2011. Assessing the Land Use Change Consequences of European Biofuel Policies. International Food Policy Research Institute, Washington, D.C., USA.

Macedo, M.N., DeFries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc. Natl. Acad. Sci. 109, 1341–1346.

Møller, J., Boldrin, A., Christensen, T.H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 813–824.

Mosnier, E., Van der Werf, H.M.G., Boissy, J., Dourmad, J.Y., 2011. Evaluation of the environmental implications of the incorporation of feed-use amino acids in the manufacturing of pig and broiler feeds using Life Cycle Assessment. Animal 5, 1972–1983.

Ocio, E., Viñaras, R., Rey, J.M., 1979. House fly larvae meal grown on municipal organic waste as a source of protein in poultry diets. Anim. Feed Sci. Technol. 4, 227–231.

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, e51145.

Prudêncio da Silva, V., Van der Werf, H.M.G., Spies, A., Soares, S.R., 2010. Variability in environmental impacts of Brazilian soybean according to crop production and transport scenarios. J. Environ. Manag. 91, 1831–1839.

Sánchez-Muros, M.-J., Barroso, F.G., Manzano-Agugliaro, F., 2014. Insect meal as renewable source of food for animal feeding: a review. J. Clean. Prod. 65, 16–27.

Šebek, L.B.J., Temme, E.H.M., 2009. Human Protein Requirements and Protein Intake and the Conversion of Vegetable Protein into Animal Protein. Wageningen UR, Lelystad, the Netherlands.

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.

Taelman, S.E., De Meester, S., Roef, L., Michiels, M., Dewulf, J., 2013. The environmental sustainability of microalgae as feed for aquaculture: a life cycle perspective. Bioresour. Technol. 150, 513–522.

Tonini, D., Hamelin, L., Wenzel, H., Astrup, T., 2012. Bioenergy production from perennial energy crops: a consequential LCA of 12 bioenergy scenarios including land use changes. Environ. Sci. Technol. 46, 13521–13530.

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, Rome, Italy.

Van Middelaar, C., Cederberg, C., Vellinga, T., Van der Werf, H.G., De Boer, I.M., 2013. Exploring variability in methods and data sensitivity in carbon footprints of feed ingredients. Int. J. LCA 18, 768–782.

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

Vellinga, T.V., Blonk, H., Marinussen, M., Van Zeist, W.J., De Boer, I.J.M., 2013. Methodology Used in Feedprint: A Tool Quantifying Greenhouse Gas Emissions of Feed Production and Utilization. Wageningen UR, Lelystad, The Netherlands.

Zwart, K.B., Oudendag, D.A., Ehlert, P.A.I., Kuikman, P.J., 2006. Sustainable Co-Digestion of Livestock Manure. Wageningen UR, Wageningen, the Netherlands.