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Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using *Hermetia illucens*

R. Salomone [a, *], G. Saija [a], G. Mondello [a], A. Giannetto [b], S. Fasulo [b], D. Savastano [c]

[a] University of Messina, Department of Economics, P.zza Pugliatti n.1, 98122 Messina, Italy
[b] University of Messina, Department of Biological and Environmental Science, Via F. Stagno D'Alcontres n.31, 98166 Messina, Italy
[c] Biosistemi Srls, SS 111 n.68, 89013 Gioia Tauro, Italy

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ABSTRACT

Food waste management strategies are mainly focused on waste minimization, but the search for new solutions to waste valorization is also a viable and potentially advantageous alternative. In this context, the aim of this study is to assess the potential environmental impacts of food-waste bioconversion into compost and dried larvae through the action of *Hermetia illucens*, by applying Life Cycle Assessment (LCA). In international scientific literature, there are many studies concerning the utilization of insects for food-waste bioconversion, but very few articles relate to the application of LCA in this sector and none of these refers to *Hermetia illucens*. Furthermore, the process of bioconversion through *Hermetia illucens* is a very attractive option, considering that it represents a potential valuable solution to two problems: food waste management on the one hand and, on the other, the rising global demand for feed (dried larvae can be used in aquaculture feed production) or the competition between land use for energy crops and for food crops (dried larvae are a fat-rich resource potentially usable for the production of biodiesel). In particular, the LCA results presented in this study refer to the assessment of the potential environmental impacts of a pilot plant in which *H. illucens* is employed for food-waste treatment. From 10 tonnes of food-waste input, 300 kg of dried larvae and 3,346 kg of compost are produced. Three different functional units were used to carry out the analysis: the input of the production process, therefore 1) food-waste; the output composed of dried larvae, for which 2) the protein content (fundamental characteristic for using this product in aquaculture) and 3) the lipid content (to be used for biodiesel production) are considered. Results related to the functional unit of 1 tonne of food waste treated show a value of 30.2 kg CO_2 eq in terms of Global Warming Potential, 215.3 MJ in terms of Energy Use, and 0.661 m^2a in terms of Land Use. When compared with alternative sources of raw material for feed or biodiesel, these results show that the most significant benefits of insect production are connected to Land Use, while Energy Use is the main burden, and the estimation of Global Warming Potential is still affected by many uncertainties.

1. Introduction

Food waste (FW) is a waste stream that is receiving growing attention due to its negative environmental, social and economic impacts (Papargyropoulou et al., 2014). Indeed, the EU estimated that FW amounts to about 100 million tonnes per annum in the EU-28 (EC, 2015; Fusions, 2015), confirming that the projection for 2020 is 126 million tonnes – an increase of about 40% (EC, 2010). According to the EU waste hierarchy (European Parliament, 2008), prevention should be the main strategy to decrease the environmental burdens from solid waste in member states. Therefore, strategies addressing the problem of FW are mainly focused on waste prevention, through improvement in the efficiency of supply and consumption chains (Schott and Andersson, 2015). However the search for solutions to their valorization is a viable and potentially advantageous alternative in a circular economy context, in which waste does not exist and organic waste should not be reduced because it is still a source of many other potential uses. Indeed, due to the energy and nutrient content of FW, lots of studies investigated the potential for its recovery in treatment processes, mainly using anaerobic digestion or composting alternatives (e.g.:

* Corresponding author.
E-mail address: roberta.salomone@unime.it (R. Salomone).

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Kiran et al., 2014; Levis et al., 2010), also with a life cycle perspective (e.g.: Lundie and Peters, 2005; Bernstadand la Cour Jansen, 2012).

In the context of waste valorisation, a promising new strategy is the utilisation of FW as substrate for mass-rearing of edible insects to be used as a protein source for the livestock sector or as a fat-rich resource for other purposes, such as the production of biodiesel. Thus, insects represent a potential valuable solution to two problems: the increasing amount of FW, which can cause environmental pollution if not managed properly, on the one hand and, on the other, the rising global demand for feed (global feed production is about one billion tonnes per annum – IFIF, 2013 – and is expected to increase) or the competition between land use for energy crops (for biodiesel production) and for food crops (Rathmann et al., 2010).

In order to properly evaluate the environmental profile of insect-based products, quantification of the environmental impacts associated with the whole life cycle of these processes should be carried out. However, very little data are available on the environmental impact associated with insect production. Indeed, in international literature, plenty of studies have investigated the nutritive composition of insects and their potential utilisation as a source of protein, both for human consumption and animal feed (e.g.: De Foliart, 1989; Bukkens, 1997; Allotey and Mpuchane, 2003; Rumpold and Schlüter, 2013; van Huis, 2013), or as a source of fats for biodiesel production (e.g.: Kumar and Sharma, 2005; Li et al., 2011; Zheng et al., 2012; Manzano-Agugliaro et al., 2012; Yang and Liu, 2014). On the contrary, there are fewer environmental studies generally focused on the value of insects in terms of sustainability and biodiversity conservation (e.g.: DeFoliart and Paoletti, 2005), and the environmental consequences associated with their mass-rearing in a life cycle perspective have been studied less (Oonincx and De Boer, 2012; van Zanten et al., 2015).

In particular, there is still a lack of a significant number of studies on the quantification of the emissions produced by insects. Indeed, very little experimental data regarding emissions from insect production are available and these data only refer to a very limited number of insect species. Indeed, from a review of English language international scientific journals, it emerges that only two studies have been published on GreenHouse Gas (GHG) emissions from insect species (Hackstein and Stumm, 1994; Oonincx et al., 2010).

Hackstein and Stumm (1994) measured methane emissions produced by more than 110 representatives of the different taxa of terrestrial arthropods. They highlighted that methanogenic bacteria occur in the hindguts of nearly all tropical representatives of millipedes (Diplopoda), cockroaches (Blattaria), termites (Isoptera), and scarab beetles (Scarabaeidae), while they are absent in 66 other arthropod species investigated by the authors. Considering that the taxa represent numerous families with thousands of species, the world populations of methane-producing arthropods constitute an enormous biomass, but there are also a great number of species that do not emit methane, such as diplopods, cockroaches, termites, locusts, crickets, springtails, bugs, bees, beetles, butterflies and flies.

Oonincx et al. (2010) estimated the production of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3) by five insect species: Tenebrio molitor, Acheta domesticus, Locusta migratoria, Pachnoda marginata, and Blaptica dubia. The study reports data both for *body mass* – calculated by averaging the body mass at the start of the experiment and the body mass at the end of the experiment – and *mass gain* – calculated as (((End mass-Start mass)/Start mass)/number of days the experiment was running) *100%. Large differences were found among these species but, comparing their emissions with those of conventional livestock, GHG emissions of four of the five insect species studied were much lower than those documented for pigs (when expressed per kg of mass gain) and only around 1% of the GHG emission for ruminants.

There is also a lack of Life Cycle Assessment (LCA) studies in this specific field of research, even though it is a relevant key tool for the evaluation of the environmental impact of production systems and insect-based products need to be thoroughly investigated, taking into account a life cycle perspective. At the time of writing of this paper, only three LCA studies have been published (Oonincx and De Boer, 2012; de Boer et al., 2014; van Zanten et al., 2015) – grey literature and articles not written in English may be missing.

Oonincx and De Boer (2012) applied the LCA to the production of two species of mealworms (*Tenebrio molitor* and *Zophobas morio*) to be used as a source of protein for human consumption and compared them with edible protein production from different conventional sources (milk, chicken, pork and beef). Results highlighted higher GHG emissions and land use associated with milk, chicken, pork and beef systems, whereas similar amounts of energy are required in conventional and mealworm protein production. In this LCA study the authors assumed the direct GHG emissions from the two investigated species of mealworms to be equal and data reported in Oonincx et al. (2010) for *Tenebrio molitor* were used; these data include CO_2 and CH_4 emissions of insects, feed and substrate.

de Boer et al. (2014) used LCA to compare different scenarios of protein production in order to investigate if soybean products from South America can be replaced by protein sources produced in Europe, without negatively affecting the carbon footprint of the feed (CFP). Among these scenarios, they also evaluated the insect option, considering meal worms as a representative of the category of insects (using the only available insect LCA at the time of their study, the one by Oonincx and De Boer, 2012). They highlighted that mealworms seemed to have little perspective for inclusion in compound feed, without increasing its CFP, because replacing 12% of soybean meal of South-American origin with 6.1% mealworms increased CFP from 595 to at least 717 g CO_2 eq per kg of compound feed. This is partly caused by the large energy requirement for heating during the production phase and the drying step. However, they also concluded that the use of other insect species (e.g. *Hermetia illucens*) with low energy requirement during rearing and higher nutrition values, reared on waste products instead of feed ingredients, may increase the replacement potential of insects.

van Zanten et al. (2015) focus on the use of housefly larvae grown on poultry manure and food waste as livestock feed. These authors concluded that energy use is the main contributor to the direct environmental impact of larvae meal production. Indirect environmental consequences entail inclusion of the environmental impact of producing the energy needed to replace the original bioenergy function of FW used for feeding housefly, and this is "situation specific" depending on the use of FW in the system under investigation (aerobic digestion, anaerobic digestion, etc.). In this LCA study, direct GHG emissions from insects are not specifically mentioned, whereas the calculation of GHG emissions related to the substrate is described in detail, distinguishing between organic waste and hen manure.

A further study (Azagoh et al., 2015), despite mentioning in the abstract "*a detailed life cycle assessment of the system*" of rearing insects on waste products, does not report any LCA inventory data and/or results in the article.

To the authors' knowledge, other research groups are currently working on the implementation of the LCA in the specific sector of mass insect rearing and other articles will soon be published in international scientific journals. In any case, it is clear that further applicative LCA studies are needed to broaden environmental knowledge on the production of insect-based products.

In this context, the aim of this study is to apply the LCA to a system of mass-rearing of *Hermetia illucens* (Diptera:

Stratiomyidae), usually known as Black Soldier Fly (BSF), grown on food waste in order to develop a detailed picture of the environmental profile of the bioconversion process and of data availability and quality.

This paper is structured as follows:

1. Introduction, summarizing the general aim of the paper, its collocation with respect to existing literature and its structure;
2. Materials and methods, explaining the analysis framework applied, divided into: description of the characteristics of the insect species under investigation and description of the assessment methods, including LCA phases (functional unit and system boundaries; inventory analysis; impact assessment) and chemical analysis carried out;
3. Results and discussion, divided into: waste reduction efficiency and bioconversion data, cradle-to-gate LCA analysis of the bioconversion process, comparative LCA of alternative systems for the production of protein and lipids, and a sensitivity analysis evaluating the effects of varying significant factors;
4. Conclusions, summarizing the main findings of the paper.

2. Materials and methods

In this section, the insect species under investigation, with its main characteristics, is presented first, then the LCA method and data are described in detail.

2.1. The insect species under investigation: Hermetia illucens (Diptera: Stratiomyidae)

The BSF (*Hermetia illucens*, Linneus 1758) is native to the warm temperate zone of America and it is now widespread in warmer regions worldwide. The larvae weigh up to 220 mg and can reach up to 27 mm in length and 6 mm in width their final larval stage. Larvae feed on decomposing organic material such as fruit and vegetable waste, as well as human and animal manure (Diener et al., 2011). Under ideal conditions (food supply, temperature, and humidity) BSF larvae can develop into prepupae within two weeks, but the developmental timing depends heavily on farming conditions. At the end of the larval stage, the prepupae empty their digestive tract, stop feeding and migrate out of the waste to find a dry site for pupation (Tomberlin et al., 2009). The females mate two days after emerging and lay their eggs in dry cracks and crevices near larval habitat (Diener et al., 2011). The adult BSF is 15–20 mm long, does not need to feed, surviving on the large fat body stored from the larval stage (Diclaro and Kaufman, 2009) and therefore does not require particular care and is not a potential carrier of diseases. As the adults are not attracted to human habitats or foods, they are not considered a nuisance and, unlike other fly species, *H. illucens* is not a disease vector (van Huis et al., 2013). BSF larvae process organic waste very quickly, restraining bacterial growth and thereby reducing production of bad odors. Moreover, the larvae are a competitor to housefly (*Musca domestica*) larvae and inhibit oviposition by the housefly, a major vector of diseases (Sheppard et al., 1994; Newton et al., 2005). Additionally, it has been suggested that the larvae contain natural antibiotics (Newton et al., 2008) and they are able to modify the microflora of manure, potentially reducing harmful bacteria such as *Escherichia coli* 0157:H7 and *Salmonella enterica* (Erickson et al., 2004).

Several methods for rearing BSF on substrates such as food wastes (Barry, 2004), pig manure (Newton et al., 2005) and poultry manure (Sheppard et al., 1994) have been developed. Optimum conditions include a narrow range of temperature (29–31 °C) and humidity (50–70%) together with an adequate oxygen supply (Barry, 2004).

2.2. The implemented method: Life Cycle Assessment

The potential environmental impacts of FW bioconversion by BSF was assessed applying the Life Cycle Assessment (LCA). LCA is a method for the identification and comprehensive assessment of the potential environmental impact associated with a material, product, service or process throughout its entire life cycle, from raw material extraction and processing, through manufacturing, transport, use and final disposal (Guinée, 2002). In accordance with ISO standards (ISO, 2006a,b) an LCA study consists of the following phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

2.2.1. Goal and scope of the study

LCA was used to study the mass-rearing and FW bioconversion by *H. illucens* carried out in a pilot plant located in Southern Italy (Fig. 1). From 10 tonnes of FW, the plant produces 300 kg of dried larvae and 3,346 kg of larvae manure. Dried larvae can be used as a source of protein for fishmeal formulation, and larvae manure as a compost equivalent to a commercial fertilizer in quality (Choi et al., 2009; Diener et al., 2011; Green and Popa, 2012). The working capacity of the plant can reach 30 tonnes/day of FW.

The goal of this study is to quantify the environmental impacts related to the production of insect-based products from mass-rearing of *Hermetia illucens* fed with FW from different sources in order to develop a detailed picture of the environmental profile of the bioconversion process and to explore the environmental impact of insect-based products compared to other conventional productions. Furthermore, LCA data availability and quality in the specific context of *Hermetia illucens* mass-rearing is evaluated.

System boundaries were defined following a cradle-to-gate approach, including four different phases: 1) transport of inputs, 2) eggs and larvae production, 3) substratum production, and 4) compost and dried larvae production (Fig. 2 – processes in dotted boxes are excluded from the analysis).

Some processes were omitted from this study due to their

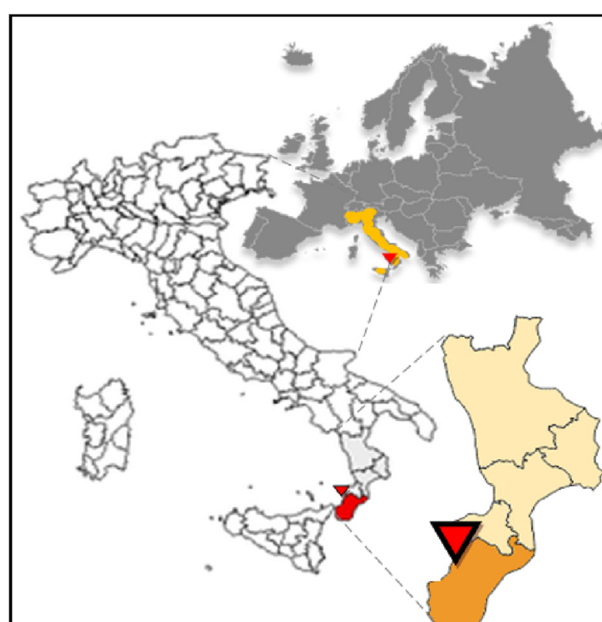

Fig. 1. Location of the pilot plant.

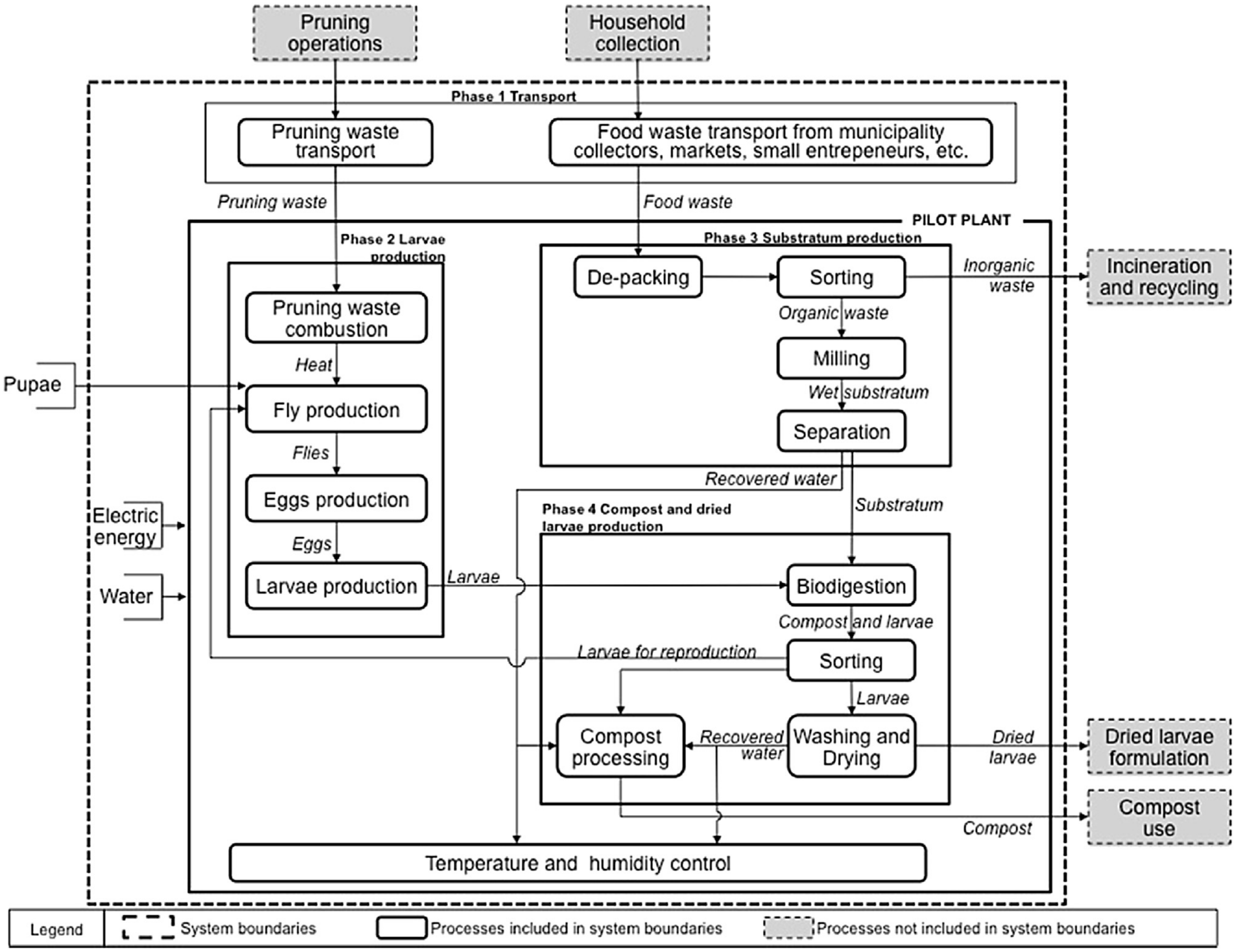

Fig. 2. System boundaries – Food waste bioconversion process.

negligible impact in relation to the goal of the study and the overall mass-rearing process.

Indeed, electricity and water consumption associated with office use was omitted because this is insignificant compared to the process-related electricity and water consumption. Disposal of inorganic waste (paper, plastic, etc.) produced in the de-packing phase was omitted because this was outside the scope of this analysis and quantitatively insignificant compared to the amount of organic waste treated (indeed only organic waste enters the plant and inorganics are of an insignificant amount and separated manually). Also big bags used for packing dried larvae were not counted, because they are returned by clients and re-used at the plant.

For similar reasons, the initial input of pupae to start the process was not taken into account, because it is irrelevant in a life cycle perspective considering that the production chain is continuously and constantly maintained by the same colony.

Methane emissions from organic waste during substrate production were omitted CH_4 emissions from organic waste occur only after several months (IPPC, 2006), but in the plant in question the substrate production is completed in one day, so these emissions are assumed to be as negligible.

Although no specific inventory data are present in published international literature concerning GHG emissions from *Hermetia illucens*, methane emissions during the biodigestion activity were omitted because, according Hackstein and Stumm (1994), Diptera (the same order as *H. illucens*) do not seem to be methane-emitting insect species.

Machinery and equipment was not taken into account, because the production of capital goods is generally excluded in LCAs of solid waste management (e.g. in the review carried out by Laurent et al., 2014, the authors highlighted that only 12% of the reviewed case studies included capital goods), but mainly because their insertion would have prevented the comparative analysis with conventional products. Nonetheless, the related processes were included in the sensitivity analysis presented in section 3.5, in order to fully investigate the consequences associated with this omission and the effective influence of capital goods from a life cycle perspective.

Considering that the mass-rearing of insects represents a potential valuable solution both for FW minimization and for the production of valuable substances (e.g. proteins to be used for feed production and lipids to be used for biodiesel production) and in order to better appreciate the different potentialities associated with the bioconversion system, and the consequences of the relevant LCA methodological choices on the results, different FUs were used in this study: 1 tonne of FW biodigested, 1 kg of proteins, and 1 kg of lipids.

The FU of *1 tonne of FW biodigested* was used in order to present a first general assessment of the bioconversion system. Choosing this FU allowed us not to apply allocation rules (as the focus is on the input of the process) and to include the avoided production of compost and fishmeal from other sources.

Two different FUs consisting of *1 kg of proteins* and *1 kg of lipids* were used in order to make a comparative assessment between the bioconversion system and conventional production systems, for proteins to be used in fishmeal production and for lipids to be used in biodiesel production respectively. In these two cases, considering that the system under investigation includes multifunctional processes, economic allocation was applied, based on the economic value of the two outputs, and, as a result, the impact of bioconversion by *H. illucens* was fully allocated to dried larvae. Indeed, the economic value of compost and larvae shows that there is a big difference in terms of price, 5–10 €·t^{-1} for compost (CIC, 2015) and about 995 €·t^{-1} for larvae (Biosistemi, 2015) respectively.

2.2.2. Life cycle inventory analysis (LCI)

The bioconversion plant consists of a large shed of about 1,800 m^2 and a surrounding area used for loading/unloading materials from trucks. Data related to one year of production at the pilot plant were considered, relating to the following three phases:

1. *transport of input materials* – in this phase the transport of FW to be treated in phase 3) and pruning waste to be used in phase 2) were considered. Organic waste comes from nine different municipalities (organic fraction from urban waste collection; waste from food chains, markets, supermarkets, shops selling fruit and vegetables, meat, fish, etc.). In order to allow the balanced composition of the substrate, organic waste entering in the plant is selected upstream, rationally alternating the FW sources. The initial input of pupae needed to start up the process occurred only once, indeed the production chain is able to constantly support itself through limited withdrawals from the larvae colony;
2. *egg and larvae production* – in this phase *Hermetia* pupae are used for reproduction. After the adults emerge from their pupal cases, their primary focus is to mate and lay eggs. They do not feed, and only drink water so only water and energy are used in this phase. The adults are kept in 12 galvanized steel aviaries (L:1.90 × W:1.60 × H:2 m) covered with mosquito nets, illuminated with white light lamps and heated with a plant powered by a boiler using pruning waste. In particular, they are kept at a temperature of 30–35 °C and humidity >65%. The adults lay their eggs inside corrugated plastic structures. A female produces about 900 eggs in her short life of 5–8 days. After oviposition, eggs take around 4 days to incubate and hatch. Generally, this phase lasts 5 days for the coupling of adults, the deposition and hatching of eggs, plus 4 days for weaning of the newly hatched larvae. A fridge is sometimes used to store the quiescent part of the colony on the basis of the needs of the processing cycle (namely if a higher or lower number of larvae is needed compared to the quantity of organic waste entering the plant);
3. *substratum production* – FW is separated manually to remove potential non-organic components. After separation the organic waste is opportunely selected and milled within a grinder in order to prepare the substrate. The average composition of the substrate is: 65% vegetal; 5% meat/fish; 25% bread/pasta/rice; 5% other. This phase occurs at ambient temperature and lasts one day. After the milling phase the substrate is placed in perforated containers in order to let the excess water pour out. In this phase 50–55% of water is eliminated. This water flows from the floor into a small collection basin containing a suction pump that stores everything in a tank. This water is not properly a leachate but rather a "slurry" as it is derived from the milling of exclusively organic waste (selected upstream) and not from mixed waste. It is important to eliminate excess water from the substrate because larvae do not bioconvert in the presence of water, rather they tend to move away. This water, plus the water used in the washing of the larval mass, is reused in the process, namely both in the compost preparation phase and in the maintenance of the humidity necessary to guarantee the optimization of the bioconversion process;
4. *compost and dried larvae production* – in this phase the substrate is distributed in fibreglass tanks, which are inserted into a steel structure by means of an electric forklift, and larvae are positioned on the substrate and are kept at a temperature of 30–35 °C, humidity >65% (the amount of larvae introduced varies depending on the type and amount of organic waste). The bioconversion process lasts about 12 days in which the larvae go through the various life cycle phases (the larva of this species is extremely voracious and is able to eat more than twice its weight in a single day). Under ideal conditions, it takes about two weeks for the larvae to reach maturity. BSF larvae pass through 5 larval stages; on reaching the pre-pupal stage the larva detaches from the substrate: larvae need to leave the manure to successfully pupate into an adult, so the separation of larvae from compost is easy. After the bioconversion, larvae and compost products are manually separated. Part of the colony is kept to evolve into pupae and maintain the production chain; the rest are subjected to a first washing in cold water (6–8 °C), to let them enter into quiescence, and then to a second washing in hot water (80 °C) and finally dried at 45 °C (using a drier of 3.3 kWh) for the removal of water by evaporation (weight reduction of approximately 60%). Washing and drying processes last about 4/5 days. In this phase, due to the lack of specific data on GHG emissions for *Hermetia illucens* in literature, we assumed that there were no methane emissions (Hackstein and Stumm, 1994), while for the other GHGs (CO_2 and N_2O), available data referred to other species were included (Oonincx et al., 2010). In particular, considering that none of the insects studied by Oonincx et al. is *Hermetia illucens* or an insect belonging to the order Diptera (on the contrary, they are all phylogenetically quite distant from *Hermetia*), data expressed in terms of body mass per day referred to *Pachnoda marginata* were assumed to be similar to *Hermetia illucens*, considering that it has a larval stage and a complete metamorphosis and feeds on decaying material, similarly to *Hermetia*.

Data sources of this study include foreground data, in which primary data were collected from the pilot plant, and background data, in which secondary data were taken from international literature and databases.

Primary data include: amount of pupae used for reproduction water and electricity; consumption; transport activities; amount of pruning waste used in the boiler; amount of FW biodigested; amount of larvae manure produced; amount of dried larvae produced; chemical composition of larvae and compost. Concerning these latter two aspects, data were measured as follows:

- at the end of the bioconversion process the prepupae were collected, weighed (wet mass) and analyzed for dry matter (DM), ash, crude protein, crude fat, and fatty acids. DM was determined after drying at 105 °C until weight remained stable and ash content after 4 h incineration at 550 °C in a combustion oven (P300; Nabertherm, Lilienthal, Germany). Total nitrogen content was determined by the Kjeldahl method (InKjel 1225 M, WD 30; Behr, Düsseldorf, Germany) and protein content was calculated by multiplying N by 6.25. Crude fat content was analyzed after extraction with petroleum ether using a Soxleth

system (R 106 S; Behr, Düsseldorf, Germany). Fatty acid composition of freeze dried prepupae was determined as described by Sealey et al. (2011) after lipid extraction using chloroform:methanol (2:1), followed by fatty acid methyl esters analysis on a gas chromatograph (Hewlett-Packard 6890 Series);
- the remains at the end of the bioconversion process, the so-called residue was weighed and lyophilized to measure dry weight. The total organic carbon (TOC) was determined by dichromate oxidation technique (Walkley and Black, 1934). The total nitrogen content was measured through micro-Kjeldahl digestion, which was followed by distillation and titration and the organic nitrogen was calculated after nitrate and ammonium extraction using a 2 M KCl solution. The extracted solutions were analysed to determine their nitrate and ammonium concentrations using a Continuous Flow Analyser. Available nutrients were estimated by Mehlich 3 extraction (Mehlich, 1984) followed by ICP-OES analysis (iCAP 6300Duo-iTEVA software, Thermo Fisher Scientific, UK). The heavy metal analysis was carried out with the high-resolution inductively coupled plasma-massspectrometer (HR-ICP-MS, Element II; Thermo Fisher Scientific), as widely described by Diener et al. (2015).

Secondary data include different data sources: due to the lack of specific data, international literature was used for pruning waste combustion (Salomone and Ioppolo, 2012) and for larvae GHG emissions (Oonincx et al., 2010), while international databases were used to calculate the eco-inventories of raw materials and energy sources (transport, tap water, electricity and energy with the Italian mix).

Data sources are specified in Table 1, while main input and output primary data per FU of 1 tonne of biodigested FW are reported in Table 2.

BSF prepupae reared on FW contain 42% crude protein and 35% crude fat (Table 3) resulting in a high-value feed source rich in protein and fat. The dry matter content of fresh larvae is quite high (37.65%) which makes them easier and less costly to dehydrate than other fresh by-products. Peer reviewed studies show that, as a component of a complete diet, BSF prepupae meal can replace at least 25% of the fish meal in a diet with no reduction in gain or feed conversion ratio in rainbow trout (St-Hilaire et al., 2007) or channel fish (Makkar et al., 2014).

Table 4 shows the prepupae fat compositions of *H. illucens* reared on FW. 16 different fatty acid methyl esters were detected and identified. The main methyl esters identified were lauric acid methyl ester (41.15%), oleic acidmethyl ester (14.07%), linoleic acidmethyl ester (13.82%) and palmiticacid methyl ester (12.50%).

Table 2
Main primary inventory data.

Description	Unit	Amount
Input		
Food Waste	t	1
Transport	tkm	24.3
Pruning waste	kg	5.5
Water	kg	61.1
Electric energy	kWh	12.9
Output		
Compost	kg	334.6
Dried larvae	kg	29.6
CO_2	kg	16
CH_4	g	51.2

Table 3
Chemical composition of *H. illucens* prepupae reared on food waste.

Protein (% on DM)	Crude fat (% on DM)	Humidity (%)	Ash (% on DM)
42	35	62.35	4.56

DM = dry matter.

Table 4
Fatty acid content (%total fatty acid identified) of *H. illucens* prepupae reared on food waste.

Fatty acid	%
Capric (C10)	1.39
Lauric (C12)	41.15
Myristolcic (C14)	0.37
Pentadecanoic (C15)	0.11
Palmitic (C16)	12.15
Palmitoleic (C16:1)	3.21
Heptadecanoic (C17)	0.17
10- Eptadecanoic (C17:1)	0.26
Stearic (C18)	2.36
Oleic (C18:1)	14.07
Linoleic (C18:2)	13.82
Arachidic (C20)	0.11
11- Eicosenic (C20:1)	0.14
11-14 Eicosadienoic (C20:2)	0.03
11-14-17 Eicosatrieroic (C20:3)	0.06
Arachidonic (20:4)	0.13

Table 1
Data sources.

Phases	Input/Output	Data sources
1. Transport	MSW transport	Primary data; Ecoinvent (Transport, lorry 7.5–16t)
	Pruning waste transport	Primary data; Ecoinvent (Transport, lorry 3.5–7.5t)
2. Egg and larvae production	Pruning waste combustion	Primary data; Salomone and Ioppolo, 2012
	Water	Primary data; Ecoinvent (Tap water, at user)
3. Substratum production	Electric energy	Primary data; Ecoinvent (Electricity, medium voltage, IT)
4. Compost and dried larvae production	Larvae GHG emissions	Primary data; Oonincx et al., 2010
	Water	Primary data; Ecoinvent (Tap water, at user)
	Electric energy	Primary data; Ecoinvent (Electricity, medium voltage, IT)
	Prepupae chemical composition	Primary data
	Compost chemical composition	Primary data

Saturated fatty acids C16 and C18, found at high values in BSF prepupae in this study, are the fatty acids with the greatest potential for biodiesel production due to their high calorific value and good potential viscosity (Manzano-Agugliaro et al., 2012). It can be concluded that BSFL can recycle waste into clean energy and reduce environmental pollution ensuring a steady production of protein and fat, both in quantity and quality, as well as price.

Chemical characterization of compost derived from FW bioconversion process by *H. illucens* prepupae showed a good potential for this material to be used as a fertilizer. The analysis reported a low humidity value of 25.7%, a pH value of 6.95 and a good balanced nutrient amount – nitrogen (N), phosphorus (P) and potassium (K) – with average NPK content of 1.49%, 0.98%, 1.03%, comparable with other organic manures. The physical quality of the product could allow easy storage, packing and transport without any further transformation or stabilization process. The agronomic characteristics and both toxic and essential metal concentrations (Table 5) showed values that fall within the limits laid down in Italian legislation (D.Lgs 75/2010 and amendments) regarding regulations on fertilizers. The results on residue reported in this study show that the compost derived from the bioconversion process by *H. illucens* is characterized by chemical and agronomic properties, namely macro and micro-nutrients, which make it an excellent bio-fertiliser without pre-post treatments.

As a result of such considerations on the chemical composition of larvae and compost, in the system using the FU of *1 tonne of biodigested FW* the avoided productions of compost and fishmeal from other sources were then included. The inclusion of avoided products, means that there is an avoided production of conventional feed or fertilizers and thereby a negative contribution to the environmental impact deriving from the bioconversion process. In particular, the following avoided productions were considered (Table 6): *soy meal* production was assumed to be the avoided product for dried larvae as both are used as fishmeal: the reference substance is the content of protein (larvae meal 48% and soy meal 46%); *nitrogen fertilizer* was assumed to be the avoided product for larvae manure since it is used as compost: the reference substance is the content of total nitrogen (larvae manure 1.49%).

In the system using *1 kg of proteins* as FU, it was not necessary to compute the amount of the edible portion to calculate the protein content, because dried larvae meal are 100% edible. The total content of protein was taken into consideration and compared with the total protein content of soybean meal (Table 7). Soybean meal was chosen for the comparison because, according to different authors (St-Hilaire et al., 2007; USSEC, 2008; Nguyen, 2008; Iribarren et al., 2012) it is widely used as fishmeal and larvae meal can be used in the diet of different fish, such as, turbot (Kroeckel et al., 2012), channel fish (Makkar et al., 2014), and rainbow trout (St-Hilaire et al., 2007).

In order to allow the comparison, the formulation of fishmeal is excluded by system boundaries, and only the phases up to the production of flour/meal, respectively from soybean and dried larvae, are taken into account when comparing the corresponding reference flow in terms of the FU *1 kg of proteins*.

In the system using *1 kg of lipids* as FU, the fat content of dried larvae is assumed to be an alternative source of fat for the production of biodiesel. The total content of lipids was taken into consideration and compared with the total lipid content of rapeseed (Table 7), because according to Karmakar et al. (2010) and Zheng et al. (2012), rapeseed is widely used for the production of biodiesel and the fats contained in larvae meal of BSF to be used for diesel production have been investigated by several authors (among the others Li et al., 2011; Manzano-Agugliaro et al., 2012; and Yang and Liu, 2014). In order to allow the comparison the production of biodiesel is excluded by system boundaries, and only the phases up to the production of seed/meal, respectively from rape and dried larvae, are taken into account comparing the corresponding reference flow in terms of the FU *1 kg of lipids*.

The relationship between reference flows and functional unit used in the comparative analysis is described in Table 8, while system boundaries of the two comparative studies are summarized in Fig. 3 (processes in dotted boxes are excluded from the analysis).

Table 5
Agronomic characteristics and metal content of the compost derived from the food waste bioconversion process by *H. illucens*.

Chemical composition	Values
Total Organic Carbon (TOC) (% DM)	31.2
Total Nitrogen (% DM)	1.49
Organic Nitrogen (% on tot Nitrogen)	90.6
C/N ratio	20.94
Phosphorus (g/100 g DM)	0.98
Potassium (g/100 g DM)	1.03
Cadmium (mg/kg DM)	0.3
Copper (mg/kg DM)	57
Nickel (mg/kg DM)	10
Lead (mg/kg DM)	54
Zinc (mg/kg DM)	206
Mercury (mg/kg DM)	0.01
Hexavalent chromium (mg/kg DM)	0.01

DM = dry matter.

2.2.3. Life Cycle Impact Assessment (LCIA)

SimaPro 8 software (Prè Consultant, 2010) was used to assess the environmental impact of the systems under consideration.

For the system using *1 tonne of FW biodigested* as FU, LCIA was conducted by means of CML 2 baseline 2000 method (CML, 2000), except for Global Warming Potential (GWP) for which the IPCC 2007 GWP 100a v. 1.02 method (IPPC, 2007) was used. This choice was determined by the fact that a higher level of detail (using different impact categories largely applied in LCA studies) for each of the phases of production considered would allow us to develop a detailed picture of the environmental profile of the bioconversion process at the plant.

For the systems using *1 kg of protein s*and *1 kg of lipids* as FUs, comparative LCIA was conducted using three main impact categories (the same used in two of the previous published LCAs on insect production – Oonincx and De Boer, 2012; van Zanten et al., 2015):

- Global Warming Potential (GWP) according to the IPCC 2007 GWP 100a v. 1.02 method (IPPC, 2007), because greenhouse emissions are a significant aspect to be measured when comparing alternative protein sources;
- Energy Use (EU), Cumulative energy demand method (VDI, 1997; Frischknecht et al., 2004), because energy consumption is indicated as the main impact both in the LCA studies of Oonincx and De Boer (2012) and van Zanten et al. (2015);
- Land Use (LU), CML 2001 (all impact categories) method (Guinée et al., 2001), because land use is a significant impact to be evaluated when comparing alternative productions, some of which involve land occupation competing with food.

3. Results, interpretation and discussion

In this section, the waste reduction efficiency and bioconversion data are presented first, then the results of the environmental impacts for the cradle-to-gate system using *1 tonne of biodigested FW* as FU are shown, followed by the results of the two comparative analyses using *1 kg of proteins* and *1 kg of lipids* as FUs. Lastly, the results of a sensitivity analysis are presented and discussed in order

Table 6
Avoided products: amount per functional unit of 1 tonne of biodigested food waste and data sources.

Reference substance	Process output		Avoided product		Data sources
	Material	Amount	Material	Amount	
Protein content	Dried larvae	29.6 kg	Soya meal	28.4 kg	Primary data; CVB, 2010; LCA Food DK – Soy meal (Nielsen et al., 2003)
Nitrogen content	Larvae manure	334.6 kg	N fertilizer	48.8 kg	Primary data; LCA Food DK – Fertiliser N (Nielsen et al., 2003)

Table 7
Protein and fat content in dried larvae of *H. illucens*, soybean meal and rape seed.

	Protein (% on DM)	Fat (% on DM)	Data source
Dried larvae	48	35	Primary data
Soybean meal	46	18.4	CVB, 2010
Rape seed	19	54.2	Yoshie-Stark et al., 2008

DM = dry matter.

to investigate the influence of data containing uncertainties and the effects of varying factors that were found to be significant in environmental terms.

3.1. Waste reduction efficiency and bioconversion data

The working capacity of the pilot plant analysed in this study showed an FW bioconversion potential of 30 tonnes per day producing 33.3% (9,990 kg/day) of residue that can be used as biofertiliser and 7.7% (2,310 kg/day) of prepupal biomass. Due to 60% humidity, prepupal biomass results in 3.1% of dry weight (930 kg/day) that can be used as an alternative to fish meal and fish oil.

Overall material reduction was calculated using the overall degradation equation:

$$D = (W - R)/R \cdot 100$$

where W is the total amount of organic material used to feed the larvae and R is the residue after the bioconversion process. A result of 66.7% was obtained. This material reduction identified in the present study is much higher than the 43.2% reported by Diener et al. (2009), where *H. illucens* larvae were reared on different daily feeding rates of chicken feed in order to assess the optimum amount of organic waste for a bioconversion system. The high overall reduction of food waste achievable by the pilot plant analysed in this study demonstrates that the standard and modular *Biosistemi* production model – characterized by the application of specific parameters (all rights reserved) – has a potential economic and environmental yield that, to the best of our knowledge, makes it unique in Europe.

3.2. Cradle-to-gate LCA analysis of the bioconversion process by Hermetia illucens

The eco-profile of the bioconversion process system with FU of 1 tonne of biodigested FW is presented in Fig. 4. In a general overview, results highlight that higher environmental impacts for each category are caused by compost and feed production (phase 4), followed by the transport phase (phase 1), except for ozone layer depletion for which transport is the main contributing phase.

Observing the single impact categories, it is possible to specify that, for example, considering the total impact related to GWP (30.2 kg CO_2 eq), the contributions of phases 1 and 4 are 5.4 kg CO_2 eq and 22.5 kg CO_2 eq, respectively, while the phases of substratum production and egg and larvae production contribute 2.1 kg CO_2 eq and 0.2 kg CO_2 eq, respectively. An examination in depth underscores that, in the transport phase (17.9% of total GWP), the transport of organic waste contributes 17.7% to total impacts; on the other hand, in compost and dried larvae production (74.4% of total GWP), the principal impacts are referred to direct GHG emissions during the bioconversion process (57.2%), while electricity consumed in the drying process contributes about 16%. Observing the other impact categories, for fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation the phase of compost and feed production contributes more than 50% to total impact (49.5%, 50.5%, 52.4%, and 55.1%, respectively), mainly due to electricity consumption for the drying process; for the remaining impacts, the contribution of phase 4 ranges from 28.4% to 43.2%.

Egg and larvae production phase (2) shows the lowest contribution for each impact category, ranging from 0.7% to 4.8%, followed by substrate production (3), which contributes for values of 7.7%–21.2%, all associated with electricity consumed in the milling process (indeed de-packing and sorting are performed manually).

Therefore, the results highlighted that energy consumption is the most significant problem in the bioconversion system, mainly due to the drying process which alone contributes to the various impact categories with values ranging from 48.9% for terrestrial ecotoxicity to 26.6% for ozone layer depletion. This is coherent with the findings of previous LCAs on insect productions (Oonincx and De Boer, 2012; van Zanten et al., 2015) which found the higher impact of energy use, although they both relate it to the required ambient temperature of the insect during the production cycle and not the drying process. On the other hand, de Boer et al. (2014) specify that the larger energy requirements are connected to the heating needs during the production phase and to the drying step. However, it should be noted that the higher energy use for ambient temperature may be connected to: a) the climatic conditions in which the investigated plants are located (for example, van Zanten et al. (2015) based their study on data from four companies in the Netherlands and therefore suggest in their conclusions that facilities should be placed in warmer climate area in order to lower EU); b) the lower energy requirement during rearing of *Hermetia illucens* with respect to the use of other insect species studied in previous LCAs.

Other impacts are mostly related to transport activities, mainly due to the transport of organic waste, a process that alone

Table 8
Reference flows and functional unit.

Case	Protein production		Lipid production		Data source
	A	B	C	D	
Reference flow	2.08 kg of dried larvae	2.17 kg of soybean flour	2.86 kg of dried larvae	1.84 kg of rapeseed	Primary data; LCA Food DK (Nielsen et al., 2003)
Functional unit	1 kg of protein		1 kg of lipids		

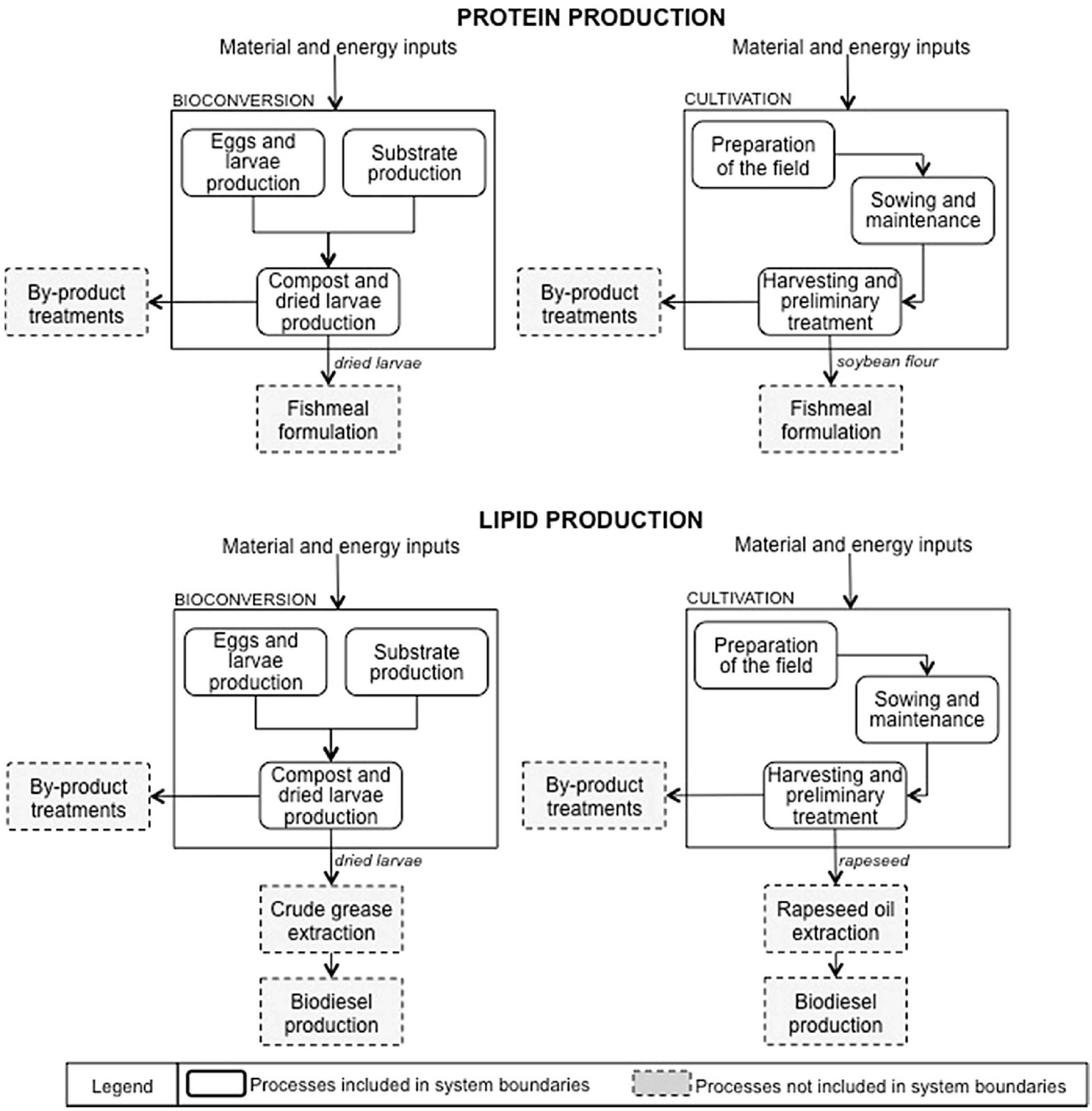

Fig. 3. System boundaries — Protein production and Lipid production.

contributes to the various impact categories with values ranging from 58.3% for ozone layer depletion to 23.9% for terrestrial ecotoxicity.

Considering that transport activities are difficult to improve (indeed FW comes only from local sources of organic waste: nine local municipalities and local food chains and markets), greater efforts should be focused on energy efficiency or on changes in energy sources alternative to electricity, as well as the use of residual heat coming from neighboring facilities.

The eco-profile of bioconversion process system with FU of 1 tonne of biodigested FW was also observed including avoided productions, thus including environmental credits associated with the avoided production of conventional feed and fertilizers. This is a normal LCA practice carried out when the system under investigation (mainly connected to recycling activities) allows avoidance of production of conventional or primary materials. Considering that the bioconversion process by *H. illucens* is observed to be a system allowing the substitution of conventional ways of providing raw materials for feed and fertilizers, the product system is credited for these forms of avoided material production, in particular, soya meal and N fertiliser related to the equivalent amount of compost and dried larvae (see Table 6). The aim is to assess the environmental impact caused by the introduction of a new production system and the replacement of a "business as usual" system, in order to understand whether the supposed environmentally friendly product has really led to a reduction in environmental impacts compared to conventional ones.

The evaluation of impacts considering avoided products shows

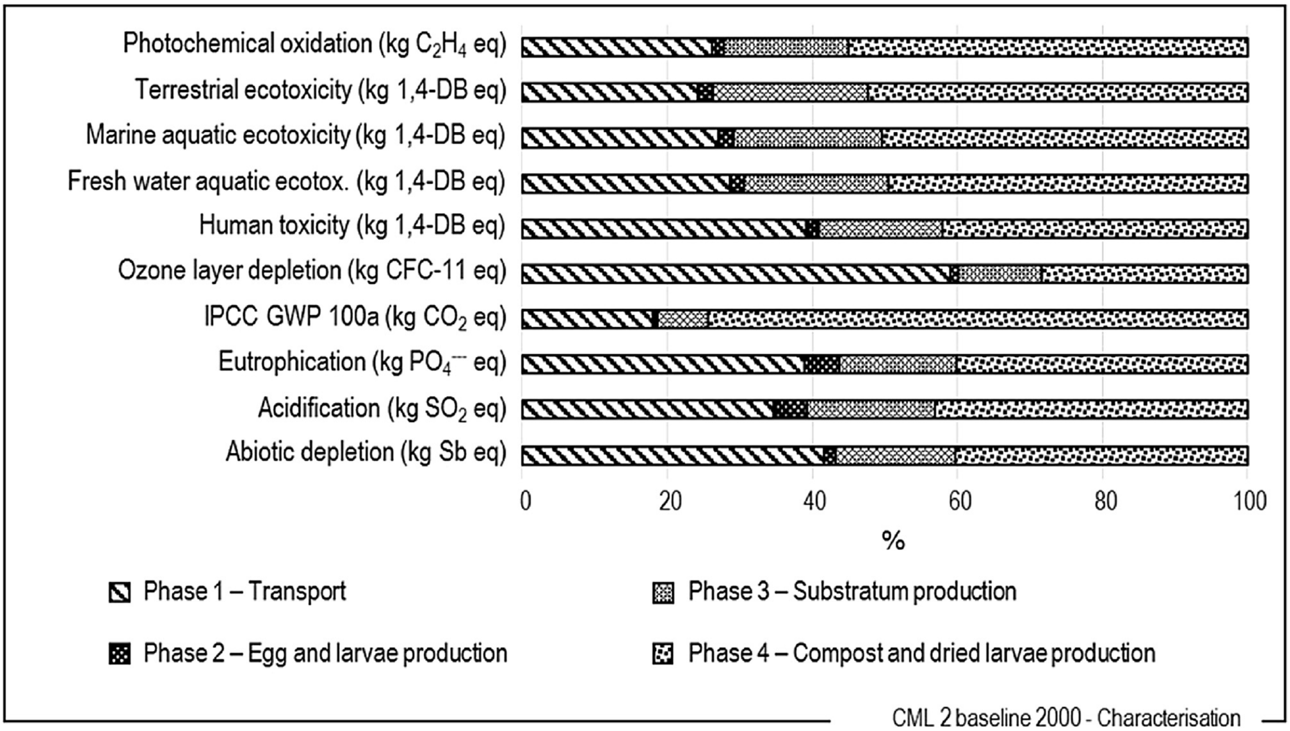

Fig. 4. Characterisation results of bioconversion process (functional unit 1 tonne of biodigested food waste).

that avoiding the production of soy meal and N fertiliser leads to many advantages in terms of environmental impacts. In Table 9, the comparison of total impact for the bioconversion system with and without avoided product computation is reported. Higher benefits are connected to GWP, for which results underline that there is a significant negative contribution to impacts (−432 kg CO_2 eq). However, it must be noted that, among GWP net savings, N fertilizer replacement accounts for about 98.7%, while soy meal replacement accounts only for 1.3%.

For all the other impact categories relatively little variation was observed, but all report a negative contribution, except for eutrophication, for which advantages are connected only to avoiding the production of N fertilizers.

The considerably higher positive contribution connected to the replacement of N fertilizer, compared to the contribution of the replacement of soy meal, depends on the higher environmental impact of N fertilizer production, but also on the fact that in soy meal production soy oil is also obtained as a by-product. This, in turn, allows replacement of rapeseed oil production (thus, replacing soy meal means that oil must be obtained from rapeseed).

Table 9
Characterisation results of bioconversion process (functional unit1 tonne of biodigested food waste with and without avoided products- AvPr).

Impact categories	Unit	Amount	
		Without AvPr	With AvPr
Abiotic depletion	kgSb eq	0.091	−1.17
Acidification	kg SO_2 eq	0.058	−1.26
Eutrophication	kg PO_4^- eq	0.014	0.036
GWP 100a	kg CO_2 eq	30.2	−432
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000014	−0.0000023
Human toxicity	kg 1,4-DB eq	3.1	−1.38
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	1.53	−0.91
Marine aquatic ecotoxicity	kg 1,4-DB eq	3,598	1,735
Terrestrial ecotoxicity	kg 1,4-DB eq	0.043	−0.028
Photochemical oxidation	kg C_2H_4 eq	0.0024	−0.021

AvPr = avoided products.

In brief, the eco-profile of the *H. illucens* system, including avoided productions, highlighted the fact that it led to a reduction in environmental impacts compared to conventional ones, but this is mostly due to the replacement of the production of N fertilizers, while the potential replacement capacity of dried larvae in terms of environmental contribution seems to be lower.

Anyhow, considering the higher economic value of dried larvae with respect to compost, the bioconversion process was further investigated choosing the impact categories considered relevant following the cradle-to-gate LCA analysis profile presented here and the previous published LCAs (GWP, EU, and LU), and FUs better suited for describing the value of dried larvae (protein and lipid content) were used.

3.3. *Comparative LCA of alternative systems for the production of protein to be used for fishmeal formulation*

To determine the potential environmental benefits associated with the production of dried larvae to be used as a source of protein for fishmeal formulation, bioconversion by *Hermetia illucens* was compared with the production of soybean flour (similarly used for fishmeal formulation) using *1 kg of proteins* as FU.

Production of 1 kg of protein by dried larvae caused a GWP impact of 2.1 kg CO_2 eq, an EU of 15.1 MJ and an LU of 0.05 m^2a. Production of 1 kg of protein by soybean caused a GWP impact of 1.7 kg CO_2 eq, an EU of 4.1 MJ and an LU of 8.7 m^2a.

Therefore, using larvae instead of soybean meal caused an increase of GWP and EU (0.4 kg CO_2 eq and 11 MJ, respectively), and a decrease of LU (8.65 m^2) (Fig. 5).

These results are in accordance with van Zanten et al. (2015), in which, using 1 tonne of larvae meal as a substitute for 0.5 tonnes of soybean meal and 0.5 tonnes of fishmeal, an increase in GWP and EU impacts, and a decrease in LU were highlighted.

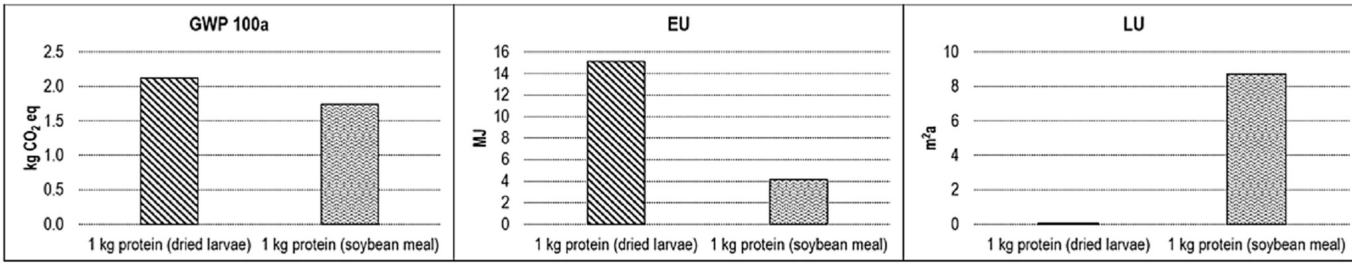

Fig. 5. Comparison between dried larvae (*H. illucens*) and soybean meal (functional unit 1 kg protein).

Therefore, when compared with an alternative source of protein such as soy meal, the *H. illucens* system entails a higher GWP impact (mainly due to direct GHGs – 57.2%) and a higher EU impact (mainly due to the transport of FW – 41.4% – and the drying process – 37.7%). On the contrary, significant benefits are connected to land use, and this is a very important aspect to be considered, since land use is one of the most significant impacts to be evaluated when comparing alternative protein productions.

3.4. Comparative LCA of alternative systems for the production of lipids to be used for biodiesel formulation

To determine the potential environmental benefits associated with the production of dried larvae to be used as a source of lipids for biodiesel production, bioconversion by *Hermetia illucens* was compared with the production of rapeseed using *1 kg of lipids* as FU.

Production of 1 kg of lipids by dried larvae caused a GWP impact of 2.9 kg CO_2 eq, an EU of 20.8 MJ and an LU of 0.06 m^2a. Production of 1 kg of lipids by rapeseed caused a GWP impact of 2.7 kg CO_2 eq, an EU of 11 MJ and an LU of 6.5 m^2a.

Therefore, using larvae instead of rapeseed caused an increase of 0.2 kg CO_2 eq (GWP) and 9.8 MJ (EU), and a decrease of 6.44 m^2a (LU) (Fig. 6).

Moreover, referring to the three main impact categories EU, GWP and LU, the results are aligned with previous evaluations and therefore confirmed the “hot-spots” of the bioconversion process as being GWP (mainly due to direct GHG emissions) and EU impacts (mainly due to the transport of FW and the drying process), while confirming LU as the main environmentally challenging factor.

3.5. Sensitivity analysis

Some of the inventory data contain uncertainties; the most significant ones are related to direct GHG emissions associated with the use of *Hermetia illucens* because, as stated in the previous discussion, no inventory data on this insect species actually exists in literature, so estimations and assumptions were made in this study. Other uncertainties are connected to the effective influence of capital goods from a life cycle perspective.

In addition, the main impacts of the bioconversion process derive from energy use (a total of 215.3 MJ related to the FU of 1 kg of FW biodigested, divided into 69.2 MJ of Primary Energy Demand and 146.1 MJ direct electricity consumption) and transport activities (GWP related to the transport phase is 5.4 kg CO_2 eq with a contribution of 17.9%): these factors should be further investigated in order to better understand the potentiality for improvement and their influence on results.

Therefore, a sensitivity analysis was performed, considering the following changes:

a) no direct emission of GHGs and emission of GHGs calculated in terms of mass gain (more relevant in comparisons of edible insect species because it gives an indication of feed conversion efficiency) instead of the body mass per day used in the base case; both are referred to *Pachnoda marginata* and reported in Oonincx et al. (2010);
b) variation of ±10% of total electricity consumption;
c) use of alternative sources of energy for the drying process (natural gas and photovoltaic);
d) variation of ±10% of transport distance;
e) inclusion of infrastructures, materials and equipment.

The sensitivity analysis was carried out firstly considering as base case the system using the FU of *1 tonne of FW biodigested* (without avoided productions) and the three impact categories of GWP, EU, and LU. Then one improvement option for each of the four variables – a) GWP mass gain; b)−10% on total electricity consumption; c) use of photovoltaic energy for the drying process; d) −10% of transport distance – was chosen and used to compare *H. illucens* dried larvae to soy meal (using the FU of *1 kg of protein*) and to rapeseed (using the FU of *1 kg of protein*); and e) the sensitivity analysis connected to infrastructures, materials and equipment was only related to the FU of *1 tonne of FW biodigested*, due to the lack of data concerning infrastructures in soy meal and rapeseed production. Results of the first four changes assumed for the sensitivity analysis are presented in Fig. 7. Please note that, the

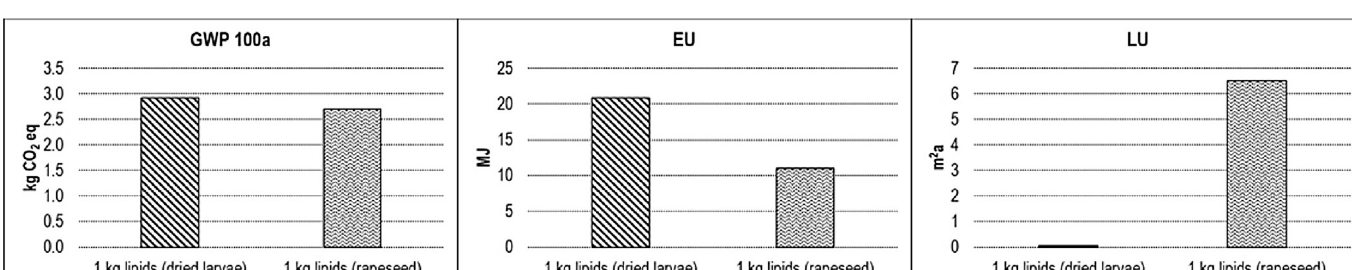

Fig. 6. Comparison between dried larvae (*H. illucens*) and rapeseed (functional unit 1 kg lipids).

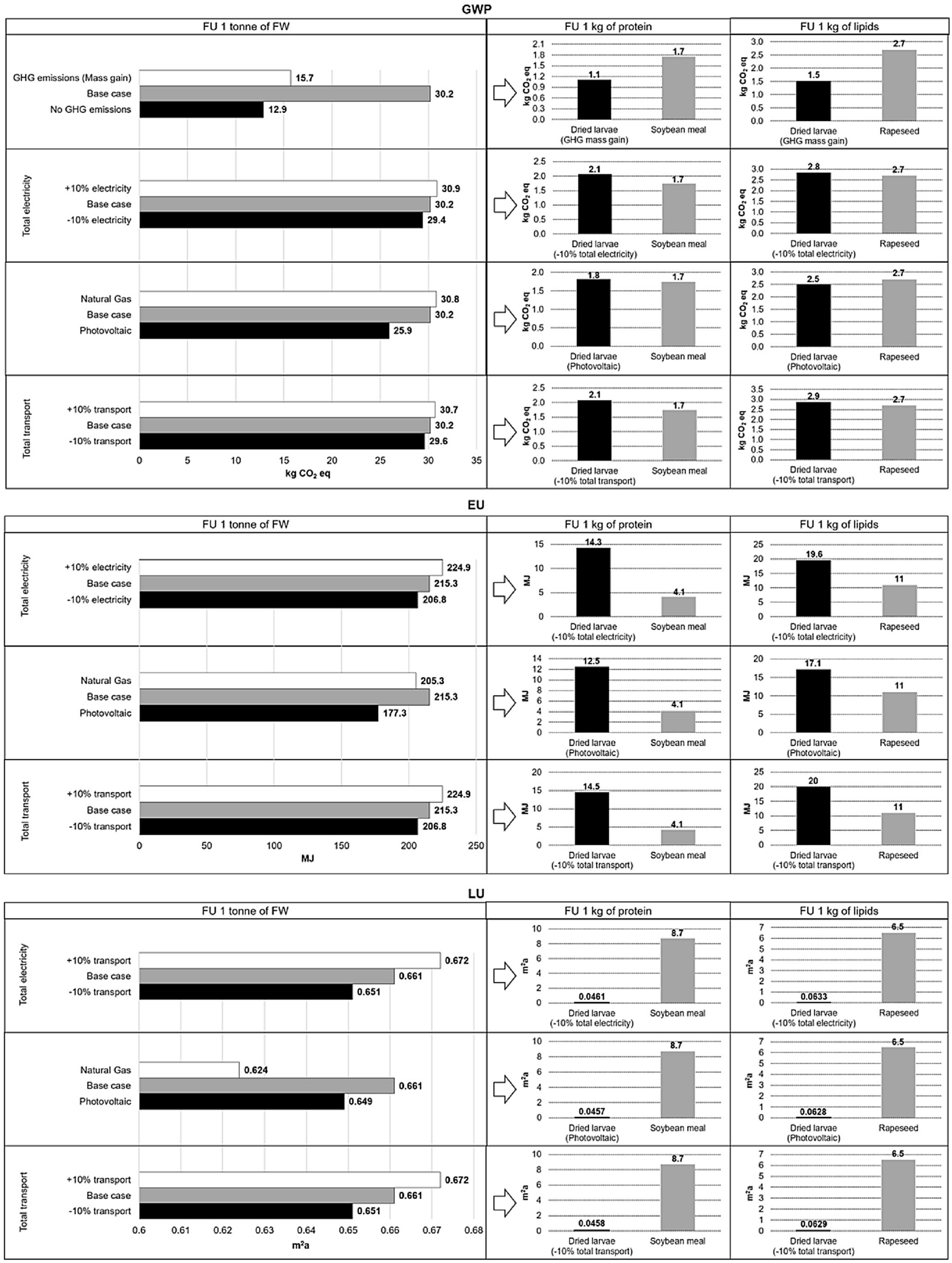

Fig. 7. Results of the sensitivity analysis.

change in direct GHG emissions does not cause variations in EU and LU, so this variable is not represented in Fig. 7 for the EU and LU impact categories. Moreover, results of the fifth change are shown in Fig. 8.

The sensitivity results highlighted some interesting findings. With respect to the variable a) "GHG emissions", the change causes a variation in GWP impacts ranging from 12.9 kg CO_2 eq (no direct emission) to 15.7 kg CO_2 eq (mass gain), while the higher value is associated with the base case for which the body mass estimation was used (30.2 kg CO_2 eq). This highlights the significant role of direct GHG estimation for evaluation of the environmental impact of the bioconversion process, which showed a variation of 57% between highest and lowest impact. Indeed, when comparing the *H. illucens* system (including an estimation of direct GHGs based on mass gain) with soy meal using 1 kg of protein or 1 kg of lipid as FU, the bioconversion process shows a lower GWP compared to proteins produced by soy meal or lipids produced with rapeseed. The variation observed in these data, and the consequent influence on results, further emphasizes that GHG data are highly sensitive and their quality and availability should be improved, considering that the only data available in literature (Oonincx et al., 2010) refer to the GHGs of only five insects species (compared to the thousands of species in the world) and these are the only data used and cited in the LCA studies so far published.

The change connected to the variable b) "±10% of total electricity consumption", reflected a change in GWP impacts from 29.4 kg CO_2 eq to 30.9 kg CO_2 eq, in EU impacts from 202.8 MJ to 227.7 MJ and LU impacts from 0.655 m^2a to 0.666 m^2a, respectively for −10% and +10%. This means that an energy efficiency improvement of 10% may cause a reduction of 2.6% for GWP, of 7.5% for EU, and of 0.9% for LU. When comparing the *H. illucens* system (−10% of total electricity consumption) with soya meal using 1 kg of protein or

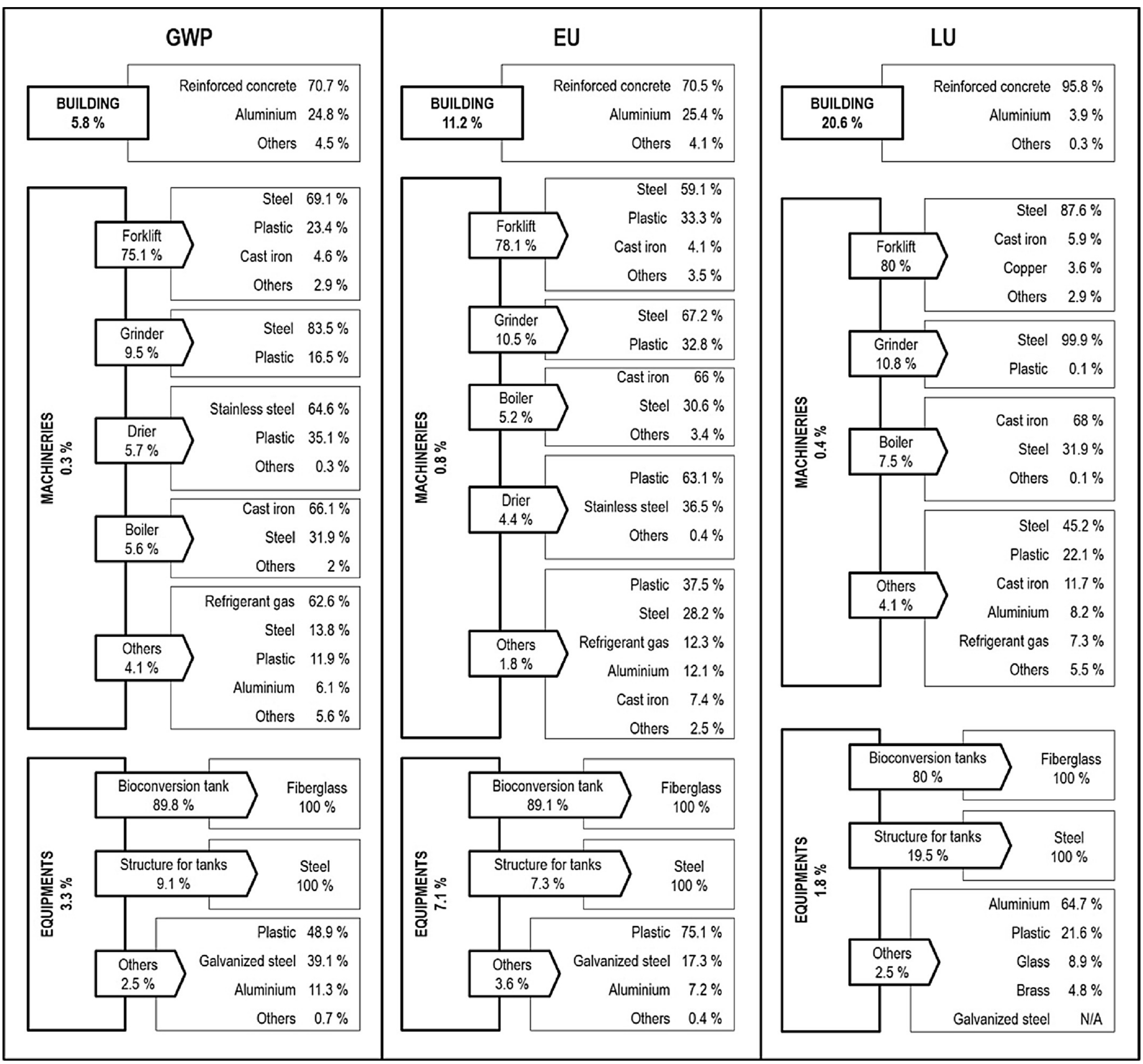

Fig. 8. Contribution analysis for building, materials and equipment (functional unit 1 tonne of biodigested food waste).

1 kg of lipid as FU, the bioconversion process shows very little variation in terms of lower GWP, EU, and LU with respect to proteins produced by soya meal or lipids produced with rapeseed.

The variable c) "natural gas/photovoltaic for the drying process" highlighted that the use of an alternative source of energy may cause a change in GWP ranging from 25.9 kg CO_2 eq to 30.8 kg CO_2 eq, in EU from 177.3 MJ to 205.3 MJ, and in LU from 0.649 m^2a to 0.624 m^2a, respectively, for photovoltaic and natural gas. Therefore, using photovoltaic energy in the drying process allows an improvement of 14.2% for GWP, of 19.2% for EU and of 1.8% for LU. This means that just this change in the drying process may cause a higher reduction of GWP and EU compared to that achievable with a 10% improvement of total energy efficiency of the whole bioconversion system. The use of natural gas in the drying process, instead of electricity, may cause lower impacts (−6.4% for EU and −5.6% for LU), except for GWP which will be higher by about +1.9%. Therefore, a total reduction of 10% of total energy consumption (through energy efficiency different strategies) would be preferable to the "natural gas" option. When comparing the *H. illucens* system (photovoltaic) with soy meal, using 1 kg of protein or 1 kg of lipid as FU, the bioconversion process shows that, despite the reduction in terms of GWP and EU, the values are still higher than those connected to systems in which proteins are produced by soya meal or lipids are produced with rapeseed, while lower impacts of LU are confirmed.

For the variable d) "±10% of transport distance", sensitivity results highlighted that these changes may cause a variation in GWP impacts ranging from 29.6 kg CO_2 eq to 30.7 kg CO_2 eq, in EU impacts ranging from 206.8 MJ to 224.9 MJ, and LU impacts ranging from 0.651 m^2a to 0.672 m^2a, respectively, for −10% and +10%. Therefore, the variation in GWP of −2% and +1.7%, in EU of −5.7% and +2.6%, and in LU of −1.5% and +1.7% shows that some margin of improvement is potentially achievable but, as stated in the previous discussion, within the context investigated in this study, transport activities are difficult to improve because all FW already comes from local facilities. Furthermore, when comparing the *H. illucens* system (−10% of transport distance)with soya meal, using 1 kg of protein or 1 kg of lipid as FU, the bioconversion process shows very little variation in terms of lower impacts, unable to reverse the outlined comparison with protein produced by soya meal or lipids produced by rapeseed.

The variable e) underscores that, with respect to the base scenario, the "inclusion of infrastructures, materials and equipment" entails an increase of total GWP, EU and LU of 9.4% (3.1 kg CO_2 eq), 19.1% (50.9 MJ) and 22.8% (0.195 m^2a) respectively per FU of *1 tonne of FW biodigested* (Fig. 8). In particular, building contributes to the total impacts with 5.8% (GWP), 11.2% (EU) and 20.6% (LU), followed by equipment (GWP 3.3%, EU 7.1% and LU 1.8%), while the lowest impacts are connected to the machinery for which all the contributions are lower than 1%. An in depth analysis showed that, the highest contribution is related to the use of reinforced concrete (GWP 1.4 kg CO_2 eq, EU 21.1 MJ and LU 0.17 m^2a) in building construction, to the steel components (GWP 0.06 kg CO_2 eq, EU 1 MJ and LU 0.0021 m^2a) in the forklift and to the fiberglass bioconversion tanks (GWP 1 kg CO_2 eq, EU 16.9 MJ and LU 0.0024 m^2a).

4. Conclusions

To the authors' knowledge this is the first LCA study on the bioconversion process by *Hermetia illucens* and this is also the first study attempting to carry out a balanced environmental evaluation connected to the nutrient, protein and lipid contents of insect-based products. Considering this lack of data, the results presented in this study are very useful for conducting a lifecycle analysis for mass insect rearing.

The main findings of the study showed that: a) higher environmental impacts are caused by compost and feed production (due to electricity consumption), followed by the transport phase (due to the transport of FW); b) energy consumption is the most significant problem in the bioconversion system, mainly caused by the drying process; c) when considering the avoided production of N fertilizers and soymeal, respectively replaced by compost and dried larvae in the *H. illucens* system, significant advantages in terms of lower environmental impacts may be obtained, mainly in terms of GWP net savings linked to N fertilizer replacement; d) when compared with an alternative source of protein such as soy meal or alternative source of lipids such as rapeseed, the *H. illucens* system entails a higher GWP impact and a higher EU impact, on the contrary, significant benefits are connected to LU; e) sensitivity results highlighted that variation in direct GHG emissions may have significant influence on LCA results, substantially reversing the comparison results outlined when comparing dried larvae with protein produced by soya meal or lipids produced by rapeseed; indeed, the bioconversion process by *H. illucens* shows a lower GWP respect to proteins produced by soy meal or lipids produced with rapeseed when the estimation of direct GHGs is based on the mass gain of insects. Considering the lack of GHG inventory data in literature, their quality and availability should be further improved; f) the change from electricity (Italian mix) to photovoltaic, only in the drying process, may cause a higher reduction of GWP and EU compared to that achievable with a 10% improvement of the total energy efficiency of the whole bioconversion system. However, even if photovoltaic energy is used for the drying process, the bioconversion by *H. illucens* still shows higher EU compared to proteins produced by soy meal or lipids produced with rapeseed; g) the inclusion of infrastructure, machinery and equipment in the system causes a significant increase in the total impacts related to the biodigestion of 1 tonne of FW, in particular due to the use of reinforced concrete in building construction, thus this aspect should be further investigated in future research activities.

The results confirmed several conclusions made in earlier LCA studies, but they also added new knowledge concerning the potential environmental impacts linked to insect-based products. Firstly, this study pointed out that significant environmental benefits are connected to the replacement of the production of N fertilizers, even though current studies on insect-based products are mainly focused on the value and role of larvae production rather than the residue of the bioconversion process (the larvae manure used as compost), also due to the higher economic value of larvae compared to compost. However, in order to appreciate the real potential of larvae manure to replace N fertilizers, their effect on field production should be explored. To the authors' knowledge there are few studies on the use of insect manure as fertilizer and further investigation needs to be undertaken in order to fully understand their effects and the possibility of obtaining a commercial product.

The study also stressed that the higher impact of energy use is mainly due to the drying process, while in previous studies (Oonincx and De Boer, 2012; van Zanten et al., 2015) it is principally caused by the required ambient temperature during rearing. The difference can be explained by the warmer climate area in which the plant is located and to the lower energy requirement during the rearing of *Hermetia illucens* with respect to location of the plant and insect species investigated in previous LCAs.

Finally, as already shown in previous studies, the most significant benefits of insect production are connected to LU, considering that insects are a raw material for feed or biodiesel that require minimal land use and, when agricultural land becomes scarce, minimal land use for the production of feed and energy may become much more important than GWP and EU. Furthermore, it should be considered that GWP assessment is still affected by many uncertainties and improvement margins for EU may still be evaluated (e.g. the use of residual heat coming from neighbouring facilities). Under these conditions, insect-based products can be very attractive, ensuring a steady production of nutrients protein and fat, both in quantity, quality and price. Thus, it would not be surprising that if the intensive BSF production were implemented on an industrial scale in the next future.

But large scale production and utilization of insect-based products still show considerable challenges in the field of *H. illucens* rearing and many uncertainties and data gaps still remain that need to be further investigated in future improvement on this field of research. In general, there is a need for more insect LCA studies, specific inventory GHG data for *Hermetia illucens* and other insect species, evaluations on the effect of the use of insect manure as fertilizer in order to better evaluate replacement of conventional fertilizers, as well as protein characterization of dried larvae and their effect on fish diet in order to better evaluate conventional feed replacement. There is also a need for legal and regulatory improvements, indeed at present, restrictive European laws concerning the use of insects in feed and food constitute the main limitation on the development of insect biorefineries despite the considerable research funds in insect-related projects.

Author contribution

Authors from the Department of Economics carried out the LCA study and authors from the Department of Biological and Environmental Science performed the chemical analysis and insect species characterization. All the authors contributed to analysis of the literature background, conclusion and writing of the paper. Biosistemi contributed to primary data and technical requirements.

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