Journal of Cleaner Production 379 (2022) 134727

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

An automated, modular system for organic waste utilization using *Hermetia illucens* larvae: Design, sustainability, and economics

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A R T I C L E I N F O

Handling Editor: CT Lee

Keywords:
Insects
Hermetia illucens
Waste processing
Food waste
Modular technology

A B S T R A C T

Large amounts of food are wasted, and valuable contents are not utilized completely. Processing such wastes into biomass of defined composition is possible using insects. However, automation and decentralization of insect-based processes are necessary for certain applications. This study presents a modular design for rearing larvae of the black soldier fly, *Hermetia illucens*. A life cycle and economic assessment are carried out to check whether the process may be viable. A sales price of 3.55 € per kg of the product would make it profitable within five years. Production of 1 kg of dried larvae would be associated with 2.77 kg CO_2 eq emitted, 55.24 MJ of non-renewable energy use, and occupation of 0.68 m^2 of organic arable land. Per kg protein, the insect biomass appears more sustainable than database benchmarks. These results indicate that even small-scale insect production processes have sustainability benefits when using food waste.

1. Introduction

931 million tonnes of food intended for human consumption was wasted in 2019, amounting to 17% of total production (United Nations Environment Programme, 2021). Large amounts of agricultural side streams such as manure, digestate, straw, or inedible plant parts (ECN, 2019; Eurostat, 2018) are produced. These residues present a significant source of biomass rich in carbohydrates, proteins, and lipids. However, procedures that recycle and recover these organic compounds are rarely implemented. Current practices use these materials as a source of energy (e.g., incineration or anaerobic digestion) or plant nutrients (after composting or anaerobic digestion). At worst, they are simply landfilled (Gao et al., 2017). These compounds could also be utilized as feedstock for producing, e.g., fine chemicals, polymers, or food and feed using chemical or biotechnological processes (Ndubuisi Ezejiofor et al., 2014). However, challenges like unknown composition (Pleissner et al., 2017) and decentralized production of these side streams (Favoino et al., 2020) remain.

One option to overcome the challenge of variable composition is to have variable biomass digested by living organisms incorporating it into their own, more well-defined biomass. Insects are commonly proposed for this purpose (Cortes Ortiz et al., 2016). A species that has received particular attention in literature for its ability to safely consume many different waste streams is the black soldier fly, *Hermetia illucens* (Nguyen et al., 2015; Wang and Shelomi, 2017). It has a promising nutrient composition, with high protein content and quality (Spranghers et al., 2017). Much research in the past has focused on the biological feasibility of rearing *Hermetia illucens* on waste biomass (Coudron et al., 2019; Lalander et al., 2018; Nguyen et al., 2015; Spranghers et al., 2017; Wang and Shelomi, 2017). These studies assess the growth and composition of black soldier fly larvae on different substrates and some of them are the basis of this study. Since this study will focus on economics and

Abbreviations: LCI, life cycle inventory; LCA, life cycle assessment; FU, functional unit; GWP, global warming potential; NRE, non-renewable energy; LU, land use; wm, wet mass; dm, dry mass.

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https://doi.org/10.1016/j.jclepro.2022.134727
Received 13 March 2022; Received in revised form 7 October 2022; Accepted 12 October 2022
Available online 15 October 2022

sustainability, previous studies in this area will be presented here.

Black soldier fly larvae are already being reared at pilot (Siddiqui et al., 2022a, 2022b; Smetana et al., 2019; Zurbrügg et al., 2018) and commercial scales (Salomone et al., 2017). Some life cycle assessments (LCA) of operating plants have been published in the scientific literature. For instance, Guo et al. (2021) found a global warming potential of 17.36 kg CO_2 eq per tonne of food waste treated for a plant with a capacity of 15 tonnes of food waste per day. Mondello et al. (2017) found a global warming potential of 71 kg CO_2 eq per tonne of food waste treated. Other LCA studies have focused on the impacts per produced product, such as the one by (Salomone et al., 2017), who found the global warming potential to be 2.1 kg CO_2 eq per kg of protein in the end product. Another study using data from a pilot plant found the global warming potential of a defatted *H. illucens* meal to be 5.33 kg CO_2 eq kg^{-1}, with 0.87 kg CO_2 eq per kg of frass allocated to the frass produced (Smetana et al., 2019).

An estimation of the economy of using *Hermetia illucens* to produce protein-rich biomass from food waste found operational costs of 1.45 € kg^{-1} of dried larvae (Pleissner and Smetana, 2020).

In the context of decentralized and small-scale processing, container-based approaches have emerged as viable methods (Ites et al., 2020). A case study for a hypothetical containerized process found waste treatment costs to range from 40.35 € t^{-1} for overdate food to 246.60 € t^{-1} for potato peels. The price required per kg of dried larvae found by the same study ranges from 3.04 € kg^{-1} when using brewery grains as feed to 7.69 € kg^{-1} when using potato peels as feed (Ites et al., 2020). Container-based pilot plants for the common housefly, *Musca domestica,* are already under operation (Bijleveld, 2021).

The system proposed and assessed in this article is based on a standard ISO shipping container (40 ft high cube) since this offers a scaffold for pre-assembly and location flexibility (Krasberg et al., 2014). energy and material balances are calculated for the life cycle assessment (LCA) and economic assessment of the presented system. This is done within the European Union (EU) geographical context, which has its own legal, market, and climatic conditions.

2. Material and methods

2.1. Process modelling

This section presents the methodology and considerations for modelling the process. This includes the biological and chemical aspects of rearing larvae. The resultant process model predicted biomass consumption and production, which enabled the creation of material and energy balances for the life cycle inventory and economic assessment.

A simplified model for larvae growth within a single tray, as proposed by Kok (2021a) and calibrated with experimental data from Lalander et al. (2019), was used to estimate the performance and productivity of the larvae. Based on different parameters of larval growth, it calculates the mass of larval biomass produced, followed by the amount of feed needed, based on the efficiency of the larvae in converting the substrate. Additional parameters were also given by this model. The metabolic heat production was estimated as the amount of energy contained in the consumed substrate (mostly in the form of protein and carbohydrates) which would not be turned into either frass or insects and would thus be released as the organic material is metabolised into CO_2, water, and Urea. Data on metabolic heat production could later be used to calculate heating and cooling requirements. The amount of CO_2 produced through the breathing of larvae was calculated based on the consumption of different substrates and the stoichiometry of the given reactions. Contrary to the methodology proposed by Kok (2021a), this study calculated the amount of air exchange needed to ensure a dry substrate at the end of the growth period by adjusting the water balance to be zero when the substrate is dry enough to be practically sievable (Dortmans et al., 2017). In cases where the needed data was not provided by the primary source (Lalander et al., 2019), other sources were used, such as for initial larva weight (Meneguz et al., 2018) and proximate composition of final larvae (Spranghers et al., 2017)). The young larvae for this process are to be reared on wheat-based chicken feed for at least five days (Meneguz et al., 2018). This rearing should be carried out by a professional contractor who would deliver the larvae to the module regularly.

Especially the initial larva weight found by different sources may not be equal. However, this was deemed acceptable since the initial larva weight (4 mg) is negligible compared to the final larva weight (212 mg). It is assumed to be a reasonable assumption that larvae starting to be fed on waste at five days old, as is practically done (Dortmans et al., 2017), can achieve the same final weights as larvae starting to be reared on food waste at ten days old.

The temperature in the container was set to 26 °C, which is in the lower range of the Optimum for *H. illucens.* The relative humidity was planned to be 66%. The feeding rates and development times were set according to practical guidelines from (Dortmans et al., 2017), but with masses and tray measurements adjusted for a 400 mm wide, 1000 mm long, and 120 mm high tray, as according to the process design, rather than the 600 mm • 400 mm surface area tray described by Dortmans et al. (2017). This simplified model does not take more dynamic parameters such as organism kinetics or system dynamics (Kok, 2021b) into account and thus does not deliver more detailed time-variable process control parameters but rather a rough general material and energy balance. Some data required by the model, like the protein content of larval waste, were not obtainable from the literature. Thus, this parameter was adjusted to make the material reduction reported by the model compatible with the observations from Lalander et al. (2019). As a result of the above considerations, one tray was modelled to receive 18,700 larvae, of which 87% would survive. These larvae would be fed a total of 26.97 kg of wet feed per tray, distributed over a total of three feedings. Considering the protein conversion ratio of 58.7% (Lalander et al., 2019), each tray was predicted to yield 16,306 larvae of 212 mg each, resulting in 3.46 kg of larvae being harvested from each tray after the 12-day growing period. The proximate composition assumed for substrate and final larvae is shown in Table 1.

These balances were further calculated for the whole process based on the design aspects of the system by multiplying the material inputs and outputs with the 320 trays in the system. To give a daily balance, these outputs were divided by the development time in days (12 days, as is practically done for optimal weight gain (Dortmans et al., 2017)). Electrical power consumption and capital and material inputs were calculated based on a list of machinery derived from the design. This list included components for the handling system and processing devices for substrate, larvae, and frass. The mass and cost for these devices were kindly provided by manufacturers wherever possible. When prices were not provided by manufacturers or online shops, they were estimated based on installed power and size.

2.2. Life cycle assessment

This section outlines how the life cycle assessment (LCA) was carried

Table 1
Proximate composition of the substrate and final larvae.

Component	Unit	Substrate (food waste)	Final larvae
Dry matter	**%**	24.3	38.1
Carbohydrates	**% dry basis**	55.0	–
Proteins	**% dry basis**	22.2	39.2
Lipids	**% dry basis**	.-	38.6
Reference		Lalander et al. (2019)	Spranghers et al. (2017)

out. It references the norms, software, databases, and methods used. The goal, scope, system boundaries, and allocation used in the LCA are also defined in this section.

In an LCA, the environmental impact of a product is assessed over its whole life cycle. This includes (depending on the scope) resource extraction, production and manufacturing of materials and energy, and end-of-life disposal. To assess all these impacts, a life cycle inventory (LCI) of the process to be assessed needs to be created first. This LCI includes the material and energy used in the production of a given amount of product and waste streams disposed of into the environment or waste treatment. A background database is required, in which the LCI for each consumed resource is given. The environmental impacts from the consumption of these products can be calculated in an iterative approach, going back to the extraction of resources for any materials used (ISO, 2006a).

The LCA was carried out according to ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) using the SimaPro 8.0.1 software (PRé Sustainability B.V., Gouda, the Netherlands) with the background LCI data from ecoinvent 3.4 (ecoinvent, Zurich, Switzerland) (Wernet et al., 2016). The life cycle impact assessment (LCIA) method IMPACT 2002+ (Jolliet et al., 2003) was used to assess the environmental impacts of this LCI. This approach aggregates the impact from all input processes according to the LCI across fifteen impact categories. Wherever possible, inputs with the geographical indication "Europe without Switzerland" were used. If no data for Europe specifically was available, "GLO" for global averages or "RoW" for global averages without Switzerland was used. All impact processes taken from ecoinvent 3 used the allocation at point of substitution (APOS) approach. A detailed LCI is given in the supplementary data.

The goal of LCA was to assess the environmental impact of the proposed system in the context of protein production and compare it to conventional benchmark protein sources. The scope of LCA was from cradle to gate, with system boundaries shown in Fig. 1. Impacts from all employed materials for the construction and running of the module and treatment of side streams such as wastewater or hydrolysis residues were considered. The use phase of produced biomass after it leaves the module was not considered. Under the allocational approach, 100% of the impact was allocated to the dried insect larvae (since the prices needing to be considered for economic allocation are uncertain). However, avoided impact through substitution of waste treatment was considered. To that end, the substitution of an ecoinvent 3 process representing the global average impacts of waste treatment was considered. This process aggregates the methods incineration, composting, and anaerobic digestion according to their market share. The functional units (FU) assessed were 1 kg of dried larvae produced (FU 1) and 1 kg of protein produced (FU 2).

The following assumptions were considered in modelling the process:

- Maintenance and cleaning were performed twice a year for a week (downtime of rearing).
- The system operated for 350 days continuously per year.
- The servicing company is located 30 km distance from the module.
- The shredder has a capacity of 320 kg h^{-1}
- The environmental impact of the production of smaller components (valves, sensors, screws, dosing pumps, etc.) is neglected

2.3. Economic assessment

This section outlines how the economic assessment was conducted to predict the required sales price of dried insects to make the process profitable.

The goal of the economic assessment was to estimate the specific cost of production and the necessary break-even price to make the investment pay back within five years. The costs included capital or fixed cost and operational, or variable cost.

The fixed cost was based on the investment cost, which is the sum of the cost of installed machinery. These investment costs were divided by the lifetime of each piece of equipment (usually twenty years) to give the annual total fixed cost. The specific fixed cost could be calculated by

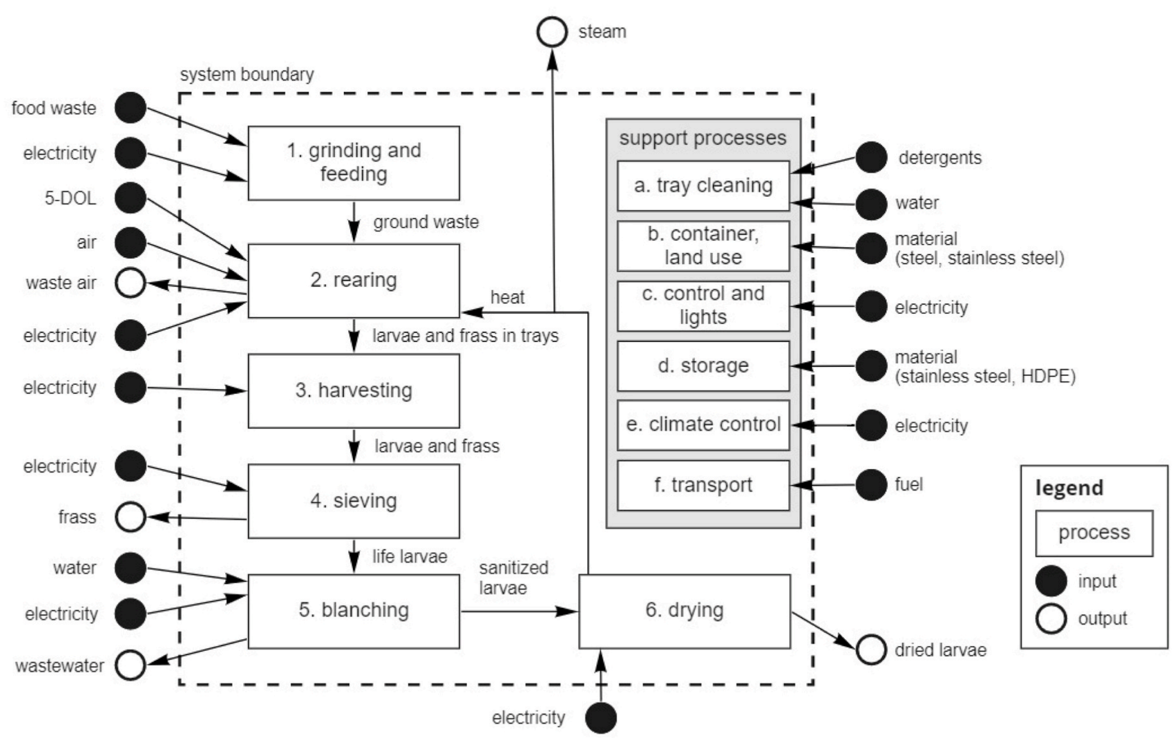

Fig. 1. Scheme of system boundaries of rearing H. illucens on food waste in the containerized module; Process steps are represented with rectangles, inputs with white circles, outputs with black circles, and the system boundary is outlined with a dashed line.

dividing the annual fixed cost by the number of dried larvae produced per year.

They were calculated based on the consumption of materials derived from process modelling. This included electricity, young larvae, water, detergents, and wastewater treatment. Labour, maintenance and transportation costs for adding young larvae and picking up product twice a week (considered to be performed by a company located 30 km away) were considered as well. Dividing these costs aggregated for one year by the amount of produced larvae gave the specific variable cost. Adding this together with the specific fixed cost gave the specific cost.

Profits for the treatment of waste with a profit of 0.07088 € kg^{-1} (including a 10% security deduction from the price used by Ites et al. (2020) and the sale of insect frass for a price of 0.69 € kg^{-1} (Illucens GmbH, 2021) were included in the calculations. Subtracting that profit from the specific variable cost gave the net specific variable cost. Adding the specific fixed cost to that amount gave the specific cost.

The breakeven cost for a payback period of five years could be calculated as: breakeven price = investment cost/5 a/annual production + net specific cost. In this manner, the breakeven price would cover the net specific cost plus a fifth of the investment cost every year, paying back the investment after five years.

3. Results and discussion

3.1. Design

For designing the *Hermetia illucens* process, established practices were the basis. The larvae are reared in trays, which can be emptied after the growth period. The challenge in this regard lies in the automatization of the process. In this study, 400 mm • 1000 mm trays are positioned on roller conveyors to allow for movement of the trays within the processing space. Fig. 2 shows a cutaway overview of the container, where the roller conveyors holding the trays (called the reactor) (2.) are visible as a system of racks (to the right), whilst in the bottom left of the picture, the processing and storage area is shown. The container contains a shelf-like structure holding eight levels of conveyors, always in two lanes side by side, such that the trays can travel from the front to the back of the container and back. Since each lane on each level of the conveyors can hold 20 trays, a total of 320 trays can be managed simultaneously. The trays can be filled with waste through a shredder (1a) from which the shredded frass moves to the top of the shelf using a screw feeder (1b) which feeds it into the trays. Then, the young larvae can be added, and the tray is pushed into the shelf using electric pusher cylinders. The trays are filled one by one and moved around the shelf for three to four days, to be fed again afterwards. This can happen multiple times over a growing period of 12 days, after which the larvae are put into a vibrating sieve (4.) which separates the frass into one container (d-1) and the insects into a cooker (5.) and later into a microwave drier (6.) for drying. The dried larvae are then filled into another container (d-2) using a conveyor belt.

3.2. Material and energy balances

Overall, a total of 29.97 kg h^{-1} wet mass (wm) or 7.28 kg h^{-1} dry mass (dm) of food waste is fed, resulting in a consumption of 719.19 kg d^{-1} (wm) or 174.76 kg d^{-1} (dm). 1.99 kg d^{-1} of young larvae need to be added. The total food waste added to one tray (26.97 kg (wm)) is turned into 3.46 kg (wm) of grown larvae and 8.05 kg (wm) of frass. After sieving, this results in a production of 92.19 kg d^{-1} (wm) of larvae and 182,43 kg d^{-1} (wm) of frass. After drying, the daily output of larvae with 4% moisture amounts to 36.59 kg d^{-1}. The dry frass production predicted by the model amounts to 44.2% of the initial substrate, giving a substrate dry mass reduction of 55.8%, which is in close agreement with that of 55.3% observed by Lalander et al. (2018) on food waste. The larvae generate 29,702 kJ of heat energy per Tray for the entire 12-day period or 792,041.73 kJ d^{-1} for the whole process. The installed electrical devices consume 162.45 kWh per day of operation or 56,879 kWh per year. This includes motors, heating, cooling, and processing equipment. The detailed LCI resulting from these material flows is given in the supplementary material.

Overall, the food waste input results in 38.79 kg d^{-1} of protein input which is turned into 13.76 kg d^{-1} of protein output in dry larvae. Thus, the overall protein conversion efficiency amounts to 35.47%. This means that more than half of the protein nitrogen ends up as nitrogen in the frass. On the one hand, this means that the objective of waste volume reduction would be achieved but on the other, that the production of food or feed is not entirely efficient. However, an advantage lies in the fact that larvae contain comparable amounts of protein ranging from 40% to 43%, no matter what substrate they are fed, in addition to good amino acid and fatty acid profiles (Spranghers et al., 2017). This results in more defined biomass suitable for more feed and food applications. The reduction of pathogens and better palatability and health benefits (Chia et al., 2020) of processed insect protein compared to food waste are also arguments for processing food waste using insects.

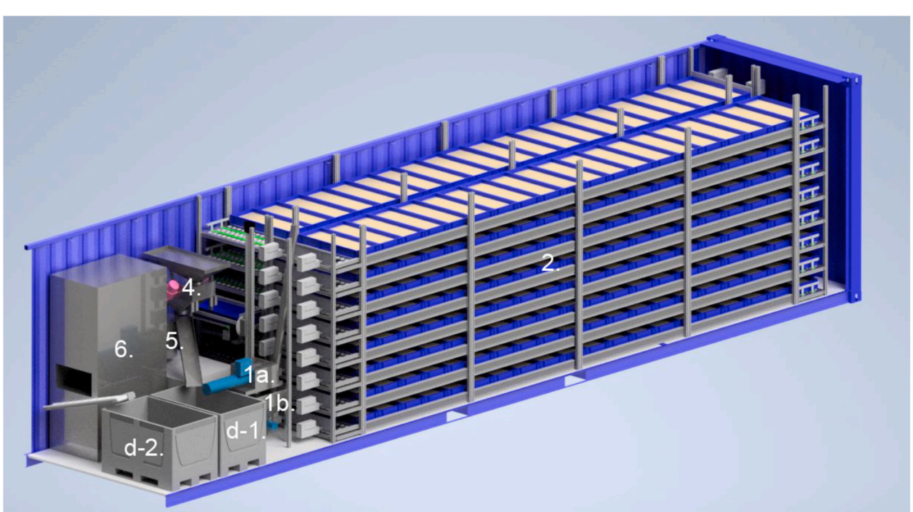

Fig. 2. Cutaway overview of the *H. illucens* rearing module. Devices are classified as follows: 1a. shredder, 1b. screw feeder, 2. reactor, 4. sieve, 5. blancher, 6. dryer, d-1 frass storage, d-2 dried insects' storage.

3.3. Life cycle assessment

The results of LCA in different impact categories are presented in Table 2. The production of 1 kg of dried insect biomass is associated with an impact on global warming potential (GWP) in the scope of 2.77 kg CO_2 eq, consumption of 55.24 MJ of non-renewable energy (NRE), and occupation of 0.68 m^2 of arable land (LU). When correcting for a protein content of 39.84% (Spranghers et al., 2017) in the dried powder to make it more comparable to other protein sources, the impact is 6.96 kg CO_2 eq, 138.65 MJ, and 1.7 m^2 of land, respectively. Compared to benchmarks in the ecoinvent 3 database, this puts the greenhouse effect below that of red meat (40.8 kg CO_2 eq per kg protein), whey (13.47 kg CO_2 eq per kg protein) and even tofu and chicken (7.78 and 9.1 kg CO_2 eq per kg protein respectively), while energy use is higher than all benchmarks except red meat (195.22 MJ) and land use lower than those of compared benchmarks. When considering the consequence of avoiding waste treatment, the impact of producing one kg of protein with the proposed system is 3.64 kg CO_2 eq (GWP), 102.67 MJ NRE used, and 1.64 m^2 of arable land. In such a case, GWP is lower than the one outlined for chicken meat (ecoinvent, Zurich, Switzerland) (Wernet et al., 2016).

Fig. 3 shows the integrated environmental impact across impact categories in comparison to different protein sources in the ecoinvent 3 database. The aggregated impact of all sub-processes taken together (2.74 mPt) is lower than for red meat (14.63 mPt), whey (4.65 mPt), tofu (3.63 mPt) and chicken (4.12 mPt). However, if the avoided impact is considered through the substitution of waste treatment, the aggregated impact (1.50 mPt) is even lower. The largest share of the total impact is caused by drying (0.89 mPt), followed by climate control (0.722 mPt).

From an environmental perspective, the LCA suggests that producing *Hermetia illucens* on food waste causes less environmental impact (per kg dried biomass and per kg protein) than conventional benchmarks, even in small to medium scale production. A comparison to the results of other studies (Table 3) suggests that the smaller scale of production is detrimental to the process's environmental friendliness. An LCA for an *H. illucens* pilot plant in Italy processing an input of up to 30 t d^{-1} found a global warming potential of only 2.1 kg CO_2 eq per kg protein in dried larvae (according to the IPCC GWP 100a methodology), with 18% of that from transport (Salomone et al., 2017). That global warming potential is much lower than the value found in this study (6.94 kg CO_2 eq kg^{-1}). This may also be explained by different production systems and assessment methodologies. A study using the same method and database on historical data from an industrial producer from the Netherlands (Smetana et al., 2019) had more comparable results: 1.8 mPt kg^{-1} for defatted *H. illucens* meal in total, with a global warming potential of 5.33 kg CO_2 eq kg^{-1}, which is less than the 2.63 mPt kg^{-1} and 6.94 kg CO_2 eq found in this study. However, that study is not quite comparable either since it allocates some of the impacts to co-products (fat and frass). When allocating all impacts to the defatted meal, the impact is almost twice as high (3.38 mPt kg^{-1}, 9.99 kg CO_2 eq kg^{-1}) and thus higher than the module proposed in this article. This can be accounted to the fact that Smetana et al. (2019) consider the impacts of feed demand since their process uses a feed that could be used for other animals as well. Substitution of that feed with non-utilized side streams (not considering any other optimizations and also excluding allocation) would mean a total impact of 2.63 mPt kg^{-1} and a global warming potential of 8.54 kg CO_2 eq kg^{-1} for the insect meal, according to Smetana et al. (2019). This would be slightly below the result from this study for the aggregated impacts (2.74 mPt kg^{-1}) but above them in terms of global warming potential (6.94 kg CO_2 eq kg^{-1}). The former appears realistic since their data refers to a larger scale. The higher global warming potential may be due to the use of natural gas rather than electricity for heating. This comparison also illustrates the importance of feed for the sustainability of insect production, as does the fact that almost the entire impact associated with the young larvae found in this study stems from their high-quality feed.

Overall, this study shows that the proposed containerized module produces insects that have a lower environmental impact per kg of protein than conventional protein sources. However, larger-scale processes tend to be more environmentally benign, unless they use natural gas heating or non-waste biomass as feed. Smaller scale appears to be detrimental to sustainability even considering the reduced need for transport. However, energy and feed source are much greater drivers of environmental impact and should be addressed first to make insects a true improvement on existing protein sources.

3.4. Economic assessment

The cost of module construction and operation are summarized in Table 4. The investment cost of 271,362.39 € results in annual fixed costs of 13,842.39 €, whilst the variable cost resulting from the use of young larvae, detergents, electricity, water, wastewater and labour for maintenance and transport comes to 51,259.73 € a^{-1}. To cover these costs, a price of 5.30 € kg^{-1} of dried biomass would be required. When including the revenue from waste treatment and frass sale, the module would generate a profit of 0.87 € kg^{-1} of dried insects produced (expressed as negative cost in Table 4). However, for the module to be paid back after five years, 3.55 € kg^{-1} of dried insects plus the projected revenue from waste treatment would be needed.

This price may be considered competitive in some food markets since Smetana et al. (2017) cite prices for meat and fish replacements between

Table 2
Environmental impact of producing 1 kg dried *H. illucens* biomass in a containerized module using food waste as substrate. Methodology: IMPACT 2002+.

Impact category	Unit	FU1: 1 kg of dried biomass		FU2: 1 kg of protein	
		No sub	Sub	No sub	Sub
Carcinogens	**g C_2H_3Cl eq**	26.23 ± 5.07	4.26 ± 8.50	65.83 ± 12.71	10.68 ± 21.33
Non-carcinogens	**kg C_2H_3Cl eq**	0.06 ± 0.02	−0.07 ± 0.08	0.14 ± 0.06	−0.18 ± 0.20
Respiratory inorganics	**g PM2.5 eq**	3.15 ± 0.18	1.20 ± 0.37	7.91 ± 0.46	3.02 ± 0.92
Ionizing radiation	**Bq C-14 eq**	120.90 ± 182.00	107.56 ± 66.79	303.47 ± 456.82	269.97 ± 167.65
Ozone layer depletion	**mg CFC-11 eq**	0.39 ± 0.04	0.26 ± 0.04	0.98 ± 0.11	0.66 ± 0.10
Respiratory organics	**g C_2H_4 eq**	0.43 ± 0.05	−0.24 ± 0.14	1.08 ± 0.13	−0.60 ± 0.34
Aquatic ecotoxicity	**kg TEG water**	230.58 ± 33.76	106.26 ± 39.86	578.76 ± 84.75	266.73 ± 100.06
Terrestrial ecotoxicity	**kg TEG soil**	85.97 ± 10.79	61.78 ± 19.36	215.79 ± 27.09	155.08 ± 48.60
Terrestrial acid/nutri	**kg SO_2 eq**	0.05 ± 0.00	−0.04 ± 0.02	0.13 ± 0.00	−0.10 ± 0.04
Land occupation	**m^2 a organic arable land eq**	0.68 ± 0.08	0.65 ± 0.74	1.70 ± 0.19	1.64 ± 1.86
Aquatic acidification	**g SO_2 eq**	14.81 ± 0.57	−6.41 ± 2.52	37.17 ± 1.43	−16.10 ± 6.33
Aquatic eutrophication	**g PO_4 P-lim**	1.18 ± 0.61	0.88 ± 0.69	2.96 ± 1.52	2.21 ± 1.73
Global warming	**kg CO_2 eq**	2.77 ± 0.07	1.45 ± 0.19	6.96 ± 0.18	3.64 ± 0.47
Non-renewable energy	**MJ primary**	55.24 ± 6.34	40.91 ± 6.11	138.65 ± 15.91	102.69 ± 15.34
Mineral extraction	**MJ surplus**	0.22 ± 0.06	0.20 ± 0.06	0.54 ± 0.16	0.49 ± 0.15

Note: No sub - all impact allocated to dried larvae as the main product, and no avoidance of waste treatment is considered; Sub - substitution of waste treatment is included; FU – functional unit; ± 5.07 – standard deviation.

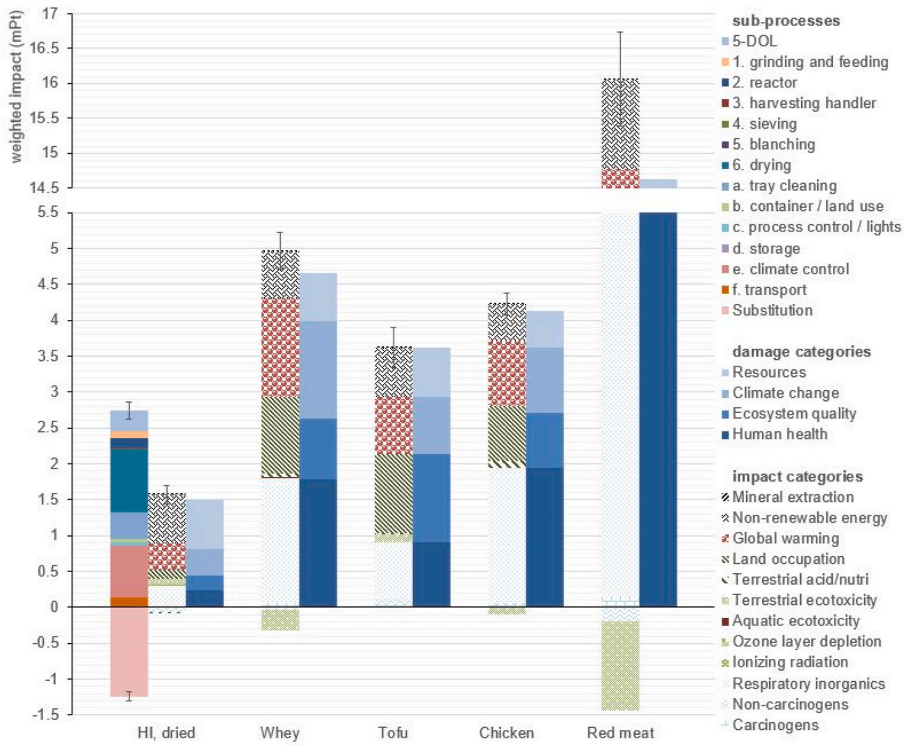

Fig. 3. Integrated impacts of the production of 1 kg of protein using *H. illucens* reared on food waste in the proposed containerized module in comparison to conventional products corrected for protein content. Sub-processes: Impacts according to material and energy consumption of process steps. Substitution of waste treatment is shown as a negative bar. Methodology: IMPACT 2002+.

Table 3
Comparison of integrated environmental impact and global warming potential for the production of *Hermetia illucens*, according to different studies.

Functional unit	Aggregated impact (IMPACT, 2002+)	Global warming potential	Reference
Unit	**mPt kg^{-1}**	**kg CO_2 eq kg^{-1}**	
1 kg protein	–	2.1	Salomone et al. (2017)
	3.38 [b, c, d]	9.99 [b, c]	Smetana et al. (2019)
	2.63 [a, c, d]	8.54 [a, c]	Smetana et al. (2019)
	2.74 [a, d]	6.94 [a]	this work
1 kg waste treated	–	0.071	Mondello et al. (2017)
	–	0.017	Guo et al. (2021)
		0.22	this work

Note: [a] using residues as substrate, [b] using animal feed as substrate, [c] with allocation to different products performed by original author removed, [d] methodology: IMPACT 2002+.

2.74 € kg^{-1} (chicken wings) to 3.99 € kg^{-1} (beef fillet). When looking at feed prices, dried insects may be a viable substitute for soybeans, at 0.35 € kg^{-1}, or fishmeal, at 1.23 € kg^{-1} average price in 2020 (World Bank, 2021). The specific cost per kg of dried insects amounting to 0.26 € could be covered by these prices, which would make the module cost neutral or slightly profitable over a period of 20 years. If the same price as for fishmeal (1.23€ kg^{-1}) could be obtained, the payback period would be 10.5 years. At the same price as soybeans (0.35 € kg^{-1}) it would be 18.13 years. But to make the module profitable within a five-year time horizon, a higher sales price of 3.55 € kg^{-1} would be needed. This price is unrealistic for the feed market and would only be competitive if prices approaching those of high-value food products could be obtained.

It should be kept in mind that these prices are for dried biomass, and when, for instance, using the biomass in an extrusion process, up to 40% water may be added (Neder-Suárez et al., 2016), reducing the price related to the input of biomass from the modules to 1.42 € kg^{-1} of the end product. The further processing of the insect biomass is thus vital to achieving an economic process and should be an area of further research.

Table 4
Results of the economic assessment of the proposed module, in which *H. illucens* larvae are reared on food waste. Costs per kg are per kg of dried larvae.

Indicator	Unit	Value
Investment cost	€	271,362.85
Total fixed cost (discount)	€ a^{-1}	13,842.39
Total variable cost	€ a^{-1}	51,259.73
Total cost	€ a^{-1}	65,102.12
Revenue waste treatment	€ a^{-1}	−17,840.36
Revenue frass sale	€ a^{-1}	−44,080.99
Specific fixed cost	€ kg^{-1}	1.13
Specific variable cost	€ kg^{-1}	4.17
Specific cost	€ kg^{-1}	**5.30**
Net specific variable cost [a]	€ kg^{-1}	−0.87
Net specific cost [a]	€ kg^{-1}	0.26
Break-even price [b]	€ kg^{-1}	**3.55**

Note: [a] subtracting revenue for waste treatment and sale of frass, [b] for a payback period of five years.

To sum up, container-based insect processing can be an economically viable method for decentralized waste treatment. However, overcoming legal and social barriers and making insects reared on wastes viable for direct human consumption is necessary to make it truly profitable and thus attractive to investors.

The sensitivity analysis (Table 5) shows that the investment cost is the most relevant factor, with a 10% increase leading to a 12.44% increase in break-even price. Electricity prices are also relevant in both cases, causing a 3.34% increase in break-even price. The relevance of frass sale (−10.11%) and waste treatment (−4.09%) to the ultimate

Table 5
Fraction of total cost caused by different cost factors as well as the sensitivity of the three indicators total cost, net specific cost, and break-even price to a 10% increase in cost (or side revenue) factors.

Factor	Fraction of total cost[b]	Indicator sensitivity to a 10% increase in the cost factor		
		Total cost	**Net specific cost**	**Break-even price**
Capital investment[a]	21.26%	2.13%	43.52%	12.44%
Electricity	22.37%	2.24%	45.79%	3.34%
Water/ wastewater	0.85%	0.08%	1.73%	0.13%
Labour	17.27%	1.73%	35.34%	2.58%
Transport	17.93%	1.75%	35.84%	2.61%
Detergent	13.02%	1.30%	26.65%	1.94%
Young larvae	7.72%	0.77%	15.80%	1.15%
Waste treatment revenue	−32.88%	–	−56.09%	−4.09%
Frass sale	−81.25%	–	−138.59%	−10.11%

Note: [a] calculated as the sum of discounts for all capital goods, [b] not including security surcharge, total cost = total annual cost of operating the module, net specific cost = specific cost of biomass production after accounting for by-product revenues, break-even price = breakeven price necessary for break-even after five years.

break-even price illustrate the increased importance of side revenues for the economy of the process. It may be concluded that using income from all three services provided by the module, that is, biomass production, waste treatment and production of fertiliser, is relevant for making it economical.

4. Conclusions

Overall, the LCA comparisons to protein benchmarks and published literature suggest that the biomass produced in the proposed process would be a more environmentally sustainable option than conventional protein sources. However, a comparison to other insect-based LCA studies shows that the small-scale process is less sustainable than established larger-scale processes. Heat source and feed are much greater drivers of environmental impact than scale. Relatively high-value products (e.g., meat replacements) would be needed to make an investment in the module profitable. The economic assessment reveals that typical prices for soybean or fishmeal would not result in a conventionally acceptable payback period for the module. The production cost also tends to be higher than for larger-scale processes. This study demonstrates that a containerized modular process is feasible from an economic and environmental point of view. Since it is not as competitive as large-scale processes it could only be used if scaling up is not an option. In addition, the implementation may be hindered by legal obstacles and social acceptance, which are aspects that must be considered in upcoming research, alongside the pilot-scale feasibility studies to test the accuracy of modelling.

CRediT authorship contribution statement

Maximilian Julius Pahmeyer: Conceptualization, Data curation, Investigation, Writing – original draft, Visualization. **Shahida Anusha Siddiqui:** Funding acquisition, Supervision, Writing – review & editing, Project administration. **Daniel Pleissner:** Validation. **Janusz Gołaszewski:** Conceptualization. **Volker Heinz:** Funding acquisition, Resources, Project administration. **Sergiy Smetana:** Funding acquisition, Conceptualization, Supervision, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This research is funded by the German Federal Ministry of Education and Research (BMBF), in the frame of FACCE-SURPLUS/FACCE-JPI project UpWaste, grant numbers 031B0934A and 031B0934B, and by the National (Polish) Centre for Research and Development (NCBiR) (Project FACCE SURPLUS/III/UpWaste/02/2020).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134727.

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