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Environmental aspects of insect mass production

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REVIEW ARTICLE

Abstract

Mass production of insects is calling for environmentally optimised and economically efficient insect value chains. It is a complex task considering a great variety in insect species, production scales, feed formulations, etc. Taking a challenge of environmental impact clarification, a few studies highlight on life cycle assessment (LCA) of insect production. The current study is aimed to systemise 24 selected previous studies to establish a modular framework for the determination of contribution of sustainability assessment factors of insect production chains. Reviewing published studies according to the elements of LCA, the study identified a feasible approach for the modelling of insect production chains, which can be used for the facilitation of comparability of further LCA studies. The approach is based on a modular analysis of insect production through a graphical mapping of value chains (allowed identification of precise system boundaries) supplemented with table analysis considering scale of production, reference (functional) unit, impact assessment methodology and type of LCA. Such an approach allows for consistency in LCA setting and further comparability of results.

Keywords: life cycle assessment, insect production chains, insect mass production, environmental optimisation, material flow analysis, sustainability

1. Introduction

Food production is facing the challenging task of assuring food security within the planet's carrying capacity. The environmental impact of the current food system should be substantially decreased (Willett *et al.*, 2019), which is extremely challenging considering the increasing demand for food in the next few decades (Gouel and Guimbard, 2019). The demand for protein sources and especially meat is projected to increase by 76% by 2050 in comparison to the basis year of 2005 (Alexandratos and Bruinsma, 2012), which will lead to critical environmental consequences. The search for alternative food and protein sources with lower environmental impact is becoming a vital task (Smetana *et al.*, 2015, 2020a; Van der Weele *et al.*, 2019) not only for the substitution of meat but also for animal protein feeds such as soybean meal and fishmeal (Van Huis *et al.*, 2013; Veldkamp *et al.*, 2012). Insects in this perspective are becoming an interesting potential solution not only for the challenges of protein supply for food and feed purposes (Van Huis *et al.*, 2013), but also for food waste treatment and nutrient recirculation in food systems (Gold *et al.*, 2020; Ites *et al.*, 2020; Mertenat *et al.*, 2019; Smetana, 2020).

While insects demonstrate the potential to deliver local and sustainable protein sources (Allegretti *et al.*, 2018; Smetana *et al.*, 2019b), the young industry of mass insect production in Western countries is still facing difficulties of setting up sustainable production starting from the design phase. There is a problem associated with data availability, which can be used for the comprehensive analysis. From one side small scale insect producers do not gather detailed data on the processes, so the data often do not exist. From another part, insect producers do not open data for the public use, so the data availability is lacking in comparison to well established feed and food industries (Bosch *et al.*, 2019; Ites *et al.*, 2020; Salomone *et al.*, 2017), which poses a challenge to the industry's efficient design of a sustainable production system (Ites *et al.*, 2020). At the same time assurance of sustainability (lower environmental impact) of insect products in comparison

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to conventional benchmarks on the market is crucial for the survival for insect mass production in Europe (Wade and Hoelle, 2020). Therefore, it is necessary to find ways for the reliable assessment of insect production at early industry development stages.

Life cycle thinking (LCT) (Fava, 1993) is a broad underlying concept, aimed at considering direct and indirect environmental impacts of complex systems, integrated into several related methods such as eco-efficiency, eco-design and life cycle assessment (LCA). Special attention to futuristic estimates is devoted in anticipatory (Guinée *et al.*, 2018), scenario-based (Fukushima and Hirao, 2002), consequential (Zamagni *et al.*, 2012), prospective or ex-ante LCA (Buyle *et al.*, 2019; Cucurachi *et al.*, 2018; Spielmann *et al.*, 2005; Walser *et al.*, 2011). They all are oriented to provide certain insights on the potential future outcomes. It should be considered that any type of prediction will include the accounting of the uncertainty, which would complicate the calculations. In order to deal with complexity issues prospective LCAs can be streamlined using a modular approach (Steubing *et al.*, 2016). Modularity of impact assessment allows for approximation of missing data values and automation of analysis (Steubing *et al.*, 2016). It is a basic concept integrated in modern LCA methods, which allows for the integrated and disintegrated analysis of production and supply chains, finding the impact hotspots and modelling of scenario effects. At the same time modularisation is not applied to insect production chains up to date.

Therefore, the main aim of this review was to establish a modular framework for the determination of environmental contribution of different parts of insect production chains (modules) based on recent literature devoted to environmental impact assessment of insect production.

In order to achieve this aim, the objectives of the paper were:

- to review current approaches to the environmental impact assessment of insect production systems, defining hotspots and the contribution of environmental impacts;
- to classify and systemise relevant environmental impact factors for modular sustainability assessment of insect production chains;
- to propose a modular framework for LCA of insect production and processing.

The article is structured to comprehensively review current literature sources dealing with production of feed for insects, insect farming, processing, and insect-based products use for food and feed purposes. It starts with explaining and illustrating the concepts of LCT and LCA. Further, the paper addresses the environmental aspects of insect production chains according to the aggregated stages of production with the aim to define the impact hotspots and assessment limitation factors. It is finalised with an overview on a potential modular framework for LCA of insect production and processing.

2. Study design

This study relies on available studies dealing with the environmental impact of insect production for food and feed, but also includes studies performing LCA on insect application for waste treatment.

The selection of studies was performed via 'Google Scholar', 'Mendeley' and 'WorldWideScience' in the beginning of 2020 using keywords: 'life cycle assessment' 'LCA' 'insect production'. The search yielded 125 studies, which were reviewed for the connection with analysis of environmental impact of insect production. Specific criteria set for the selection of studies were that is should contain an original LCA model of insect-based production of feed or food, waste treatment or other system aimed for insect production. One output of insect production system is the insect biomass, which is quantified. Design of insect production system should include the reproduction cycles and not rely on natural oviposition or natural insect harvesting. The review excluded the studies which do not include reflection on mandatory elements of LCA: goal and scope definition, life cycle inventory (LCI), functional unit (FU), life cycle impact assessment (LCIA) methods and interpretation. The references of the articles suitable under defined criteria were also explored for consistency. The review then concentrated on the analysis of selected articles (24). The selected articles reviewed in this manuscript follow the life cycle approach and include insect production stages, upstream and in some cases downstream processes. They all define goal and scope, system boundaries, provide inventory data and draw conclusions on the impact of a product as well as hotspots of production.

The review article will follow the conceptual approach applied to all the LCA studies. All the subchapters start with defining the goal and scope, specifying the reasons for separation and analysis of the production stage (module), boundaries for the module and limitations of such selection. Furthermore, data availability and requirements will be analysed as well as potential approaches for data collection, validation and aggregation for the input and output data to quantify material use, energy use, environmental discharges, and waste associated with each module. The final part of modules and sub-modules analysis will include the analysis on the use of LCIA methods, categories, indicators, equivalency and contribution factors. Critical analysis on the interpretation of results and drawn conclusions in current studies will be a closing part.

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3. Life cycle assessment

LCT approach is aimed at a holistic conceptualisation of environmental issues (or other pillars of sustainability) at system level (Mont and Bleischwitz, 2007). LCT is a holistic approach, which examines the impacts of a product or a service through its entire life cycle from the extraction of raw materials (cradle), through production, use and final disposal or other end of life options (grave) (UNEP/SETAC, 2012). It means that the sustainability analysis considers required resources and expected impacts of all life cycle stages (design, production, use and end of life). LCT provides a comprehensive basis for the analysis of indirect and rebound effects, allowing to eliminate unintended negative consequences associated with higher rates of consumption of environmentally efficient and cheaper products (Hertwich, 2008; Mont and Bleischwitz, 2007). Classical applications of LCA relate to the determination of environmental impact of product through the entire life cycle of a product, identification of environmental hot spots (stages with the highest contribution), product comparison, eco-design and other aspects. The comparison of alternative products and minimisation of trade-offs between them, for the selection of less environmentally impacting options (Cucurachi *et al.*, 2019), became a 'golden' standard in environmental assessment of products and services. Moreover, LCA is a basis for Environmental Product Declaration (Del Borghi, 2013; Schau and Fet, 2008) and Product Environmental Footprint (Bach *et al.*, 2018), included in the guidelines of European Commission for the environmental impact assessment and declaration (Allio, 2007). The development of the European guidelines further triggers practical application of LCA for business and management strategies, marketing and product labelling (Mont and Bleischwitz, 2007; Rubik and Frankl, 2017).

LCA is a complex method, which requires a high-level knowledge, related to the method and dealing with environmental impact concepts and guiding factors. ISO standards define four main stages of LCA: (1) goal and scope definition; (2) LCI; (3) LCIA; and (4) interpretation (ISO 14040, ISO 14044; ISO, 2006a,b). Any LCA should include information on FU, system boundaries, impact assessment methods and timeframe (Thabrew *et al.*, 2009), but also details on assumptions, limitations, data quality and requirements, reference flows, etc. LCIA methods assign an impact factor to an elementary flow in the inventory, thus connecting the amount of resources used and emissions to the potential environmental impact caused (Zampori *et al.*, 2016). Moreover, two main approaches in completing LCA should be outlined: attributional (information on environmental burden associated with the specific product life cycle) and consequential (information on environmental burden appearing because of decision making with consequences of the market changes) (UNEP/SETAC, 2011). Goal and scope of the study define the type of approach to be followed. Some studies focus on an attributional LCA, others on a consequential LCA, and others on both, attributional and consequential. Such conceptualisation allows for certain consistency between different studies and standardisation of results. Further chapters include a few examples on the indicated components in relation to insect production chains.

Modularity of LCA is foreseen as a feasible way of dealing with many variants in a product's life cycle (Jungbluth *et al.*, 2000). The approach allows to assess multiple alternative value chains within a production system. In LCA a product's life cycle is modelled in various boundaries (depending on the goal and scope of the study: from cradle to grave, cradle to gate, gate to gate, etc.), to set some pre-conditions for the comparability of the studies in the same scope. To compare alternative value chains, each alternative life cycle needs to be modelled individually, even if changes were made only in one of the stages. By contrast, the fundamental idea of the modular LCA approach is to break down a production system or a product's life cycle into modules which can be recombined to form complete value chains (Steubing *et al.*, 2016). These modules are practitioner-defined and encompass life cycle stages or unit processes. Besides elementary flows, the modules only have input and output flows which link them to other modules of the studied production system. This is achieved by expanding a module's foreground process(es) to include all required background processes (e.g. utilities, waste treatment, infrastructure). This procedure is repeated until the entire production system is described in modular LCI. Based on these modular LCIs, LCIA is carried out, leading to individual LCIA results for each module. The LCIA result for a value chain is determined by aggregating the LCIA results of the involved modules (Rebitzer, 2005).

When several modules within a production system produce substitutable products, alternative value chains arise. A module-product matrix contains information on how the modules can be connected to form alternative value chains, taking scaling factors and interdependencies into account (Steubing *et al.*, 2016). An advantage compared to conventional LCA is that the modelling effort can be considerably lower, since it scales with the number of modules, not with the number of alternative value chains. However, the modular approach requires an up-front time investment for the modularisation, meaning the suitable definition of modules to represent key choices within the production system. Modular LCA can therefore streamline (aggregate) scenario analysis through the optimisation models, which allow for the identification of missing data points using optimisation algorithms (for example using Pareto optimisation). It can therefore not only enable optimisation of value chains by using the module data as inputs to optimisation models (Steubing *et al.*, 2016) but also can provide solutions for the data limitations in the assessment of emerging technologies (Thomas *et al.*, 2020).

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4. Environmental hotspots of insect production

Overall, the available studies rely on a few approaches towards the LCA of insect production. Most of the studies use an attributional approach for the analysis, aimed at the identification of hotspots and comparison with similar products (Table 1). Only two studies take first steps towards consequential assessment of insect production, indicating the difficulties and high uncertainty rates associated with assumptions concerning product substitutions on the market (Smetana *et al.*, 2019b; Van Zanten *et al.*, 2018).

Most studies employ multiple impact categories and characterisation factors (coefficient units allowing equivalent aggregation of the environmental interventions to a particular impact category) to analyse the environmental impact of insect production. A wide variety of impact assessment methods is used. Separate indicators are mostly calculated in early studies (Joensuu and Silvenius, 2017; Komakech *et al.*, 2015; Oonincx and De Boer, 2012; Van Zanten *et al.*, 2015), while other studies rely on more aggregated methodologies, allowing for the inclusion of multiple indicators and end-point aggregation (Table 1).

Setting the goal and scope of the study is of outmost importance for any LCA study, as mistakes at the selection of FU or system boundaries could lead to wrong results and justifications (Rebitzer *et al.*, 2004). LCA studies of insect production chains are not exception. The general goal in the studies reflecting on the production of insects grown on conventional (commercial) feed is connected with identification of environmental impact of such production with certain comparison to similar protein production systems (Halloran *et al.*, 2017; Oonincx and de Boer, 2012; Smetana *et al.*, 2016, 2019b; Suckling *et al.*, 2020) for food and feed purposes. Strong comparative approach based on a few FUs to conventional 'traditional' protein and fat sources is taken in studies of Smetana *et al.* (Smetana *et al.*, 2015, 2016, 2019b, 2020a). Special attention in some studies is devoted to the identification of insect production impact if by-products are applied for the feeding (Bava *et al.*, 2019; Maiolo *et al.*, 2020) in these cases considering

Table 1. Life cycle impact assessment approaches in life cycle assessment studies of insect production.

Study	Impact categories (characterisation factor)[1]	Impact assessment method	Attributional/ consequential
Smetana *et al.*, 2020a	Multiple mid and endpoint	IMPACT 2002+ Version 2.21	Atr
Suckling *et al.*, 2020	Multiple midpoint	ILCD 2011 Midpoint+ method	Atr
Ites *et al.*, 2020	Multiple mid and endpoint	IMPACT 2002+ Version 2.21	Atr
Maiolo *et al.*, 2020	GWP, AP, EP; CED, WU	CML-IA baseline V3.05, CED (Frischknecht *et al.* 2007); AWARE	Atr
Roffeis *et al.*, 2020	Single score	ReCiPe method (V 1.11)	Atr
Ulmer *et al.*, 2020	Multiple mid and endpoint	IMPACT 2002+ (V 2.11)	Atr
Bava *et al.*, 2019	Multiple midpoint	ILCD 2011 Midpoint V1.03	Atr
Smetana *et al.*, 2019b	Multiple mid and endpoint	IMPACT 2002+ and IMPACT World for WF; ReCiPe for sensitivity	Atr, Cons
Van Zanten *et al.*, 2018	GWP, EU, LU	Separate indicators	Atr, Cons
Mertenat *et al.*, 2019	GWP	ReCiPe Midpoint (H)	Atr?
Bosch *et al.*, 2019	GWP, LU, EU	Separate indicators	Atr
Thévenot *et al.*, 2018	CED, CC, AP, EP, LU	CED was quantified using the Total Cumulative Energy Demand method v1.8 (VDI, 1997). CC, AP, EP, and LU were calculated according to the CML-IA baseline 2000 V2.03 method	Atr
Halloran *et al.*, 2017	Multiple midpoint	ILCD method	Atr
Roffeis *et al.*, 2017	Single score	ReCiPe method (V 1.11)	Atr
Salomone *et al.*, 2017	GWP, LU, EU	CML 2 baseline 2000 method and GWP 100a v. 1.02 method (IPPC, 2007)	Atr
Joensuu and Silvenius, 2017	GWP	Separate indicators	Atr
Smetana *et al.*, 2016	GWP, EU, LU; single score	ReCiPe V1.08 and IMPACT 2002+	Atr
Roffeis *et al.*, 2015	ALO, WD, FD	ReCiPe 2008	Atr
Smetana *et al.*, 2015	Multiple mid and endpoint	IMPACT 2002+	Atr
Van Zanten *et al.*, 2015	GWP, EU, LU	Separate indicators	Atr
Komakech *et al.*, 2015	GWP, EP, EU	Separate indicators	Atr
Oonincx and De Boer, 2012	GWP, LU, EU	Separate indicators	Atr

[1] ALO = agricultural land occupation; AP = acidification potential; CC = climate change; CED = cumulative energy demand; EP = eutrophication potential; EU = energy use; FD = fossil depletion; GWP = global warming potential; LU = land use; WD = water depletion; WU = water use.

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insect production for feed or petfood purposes mostly (Bava *et al.*, 2019; Maiolo *et al.*, 2020; Smetana *et al.*, 2016, 2019b; Thévenot *et al.*, 2018). On the other hand, insects as by-product of honey production are analysed in study of Ulmer *et al.* (Ulmer *et al.*, 2020). Separate goal is set in the studies dealing with insect production for waste treatment including manure treatment (Ites *et al.*, 2020; Komakech *et al.*, 2015; Mertenat *et al.*, 2019; Roffeis *et al.*, 2015; Salomone *et al.*, 2017) and further animals grown on insects (Van Zanten *et al.*, 2015). More prospective approach is presented in studies dealing with ex-ante and consequential assessment (Roffeis *et al.*, 2017; Smetana *et al.*, 2019b), and evaluation environmental performance of insect production in regional perspective (West Africa) (Roffeis *et al.*, 2020).

Analysed studies rely on various FU (Bava *et al.*, 2019; Salomone *et al.*, 2017; Smetana *et al.*, 2015, 2019b; Ulmer *et al.*, 2020). Weight-based units dominate in the studies; however, they reflect different aspects of insect production. Some studies account for the weight the input materials in case of waste or manure treatment to determine efficiency of biotransformation(Ites *et al.*, 2020; Komakech *et al.*, 2015; Mertenat *et al.*, 2019; Roffeis *et al.*, 2015; Salomone *et al.*, 2017). Studies dealing with production of insect-based feed (Maiolo *et al.*, 2020; Roffeis *et al.*, 2017, 2020; Thévenot *et al.*, 2018; Van Zanten *et al.*, 2015) or insect-based ingredients for food and feed purposes (Halloran *et al.*, 2017; Smetana *et al.*, 2015, 2016, 2019b; Suckling *et al.*, 2020; Ulmer *et al.*, 2020) rely on weight-based unit of output product (feed, meal, insects, dried insects). In order to consider nutritional properties of insects studies rely on comparison based on amount of proteins (Bosch *et al.*, 2019; Halloran *et al.*, 2017; Joensuu and Silvenius, 2017; Oonincx and De Boer, 2012; Salomone *et al.*, 2017; Smetana *et al.*, 2015, 2016, 2019b; Ulmer *et al.*, 2020), lipids (Salomone *et al.*, 2017; Smetana *et al.*, 2019b, 2020a) or energy (Smetana *et al.*, 2015).

The overall reliability of data in the analysed studies could be assessed as good, as a lot of studies relied on primary data for foreground processes of insect production (Bava *et al.*, 2019; Halloran *et al.*, 2017; Oonincx and De Boer, 2012; Roffeis *et al.*, 2017, 2020; Salomone *et al.*, 2017; Smetana *et al.*, 2019b; Suckling *et al.*, 2020; Thévenot *et al.*, 2018; Ulmer *et al.*, 2020), a few studies relied on mixed literature and primary measured data (Ites *et al.*, 2020; Maiolo *et al.*, 2020; Mertenat *et al.*, 2019; Smetana *et al.*, 2016). The studies, which have a hypothetical or review character relied on secondary modelled data or literature sources for the modelling of LCA (Bosch *et al.*, 2019; Komakech *et al.*, 2015; Roffeis *et al.*, 2015; Smetana *et al.*, 2015; Van Zanten *et al.*, 2015).

The differences in the goal and scope between different studies indicate that it is not viable to compare the results between all of them, as system set for the prime quality insect biomass production would be different from the system oriented solely on waste treatment. A bright example could be the studies of Roffeis *et al.* (2015, 2017, 2020) where the high impact of insect production could relate to a regional approach taken, not available in other studies. Selection of FUs applied in the studies demonstrate consistency with reliance on weight basis in most studies. Differences presented of weight units routed in the magnitude or concentration on various parts of insect production chains (input or output) can be levelled through the recalculation for the same unit. Reliability of data used for the LCA studies is assured using primary data from the production. If the direct measured data is not available, the studies rely on modelling or literature sources. In these cases, reliability and availability of data is of higher importance to be analysed.

Feed for insects

Type of feed selected (vegetable rests, compound feed, food waste, etc.) and properties of selected feed (nutrient content, moisture content) in a great degree define the performance and environmental impact of the insect production system (Bosch *et al.*, 2019; Ites *et al.*, 2020; Oonincx and De Boer, 2012; Smetana *et al.*, 2016, 2019b). And this relation is not straightforward. High quality of feed for insects in many cases results in higher environmental impact, but also comparatively short growing cycles. While lower nutritional quality of insect feed (which could have a lower impact of production) results in smaller size of insects, longer growing cycles and higher conversion ratio (Bosch *et al.*, 2019; Smetana *et al.*, 2016). This is the first trade-off which producers should consider. Moreover, the system is further complicated with the potential of insect application for waste treatment. Treatment of food waste may result in environmentally beneficial results especially if the feeding substrate is of good nutritional quality (Bosch *et al.*, 2019; Ites *et al.*, 2020; Salomone *et al.*, 2017; Smetana *et al.*, 2016). Environmental impact of animal manure treatment with insect technologies could also result in positive or negative environmental impact depending on the impact of avoided treatment processes (Roffeis *et al.*, 2017, 2020; Smetana, 2020; Smetana *et al.*, 2016).

Primary production of feed (feed ingredients)

LCA studies of insect mass rearing rarely pay attention to the variations of feed production or to the side-streams (by-product) allocation of impacts. A lot of insect producers rely on the commercial compound feeds due to the legislative limitations (Bosch *et al.*, 2019). Thus, it is necessary to pay careful attention to modelling of feed crops harvesting and feed production. In case of commercial feed production, the boundaries for insect feed are comparable to those

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outlined for animal feeds (Bava *et al.*, 2019; Bosch *et al.*, 2019; Halloran *et al.*, 2017; Smetana *et al.*, 2016). The boundaries should include the classic agricultural stages of sowing, growing and harvesting with further processing into animal feed. High availability of data and previously performed analyses (McAuliffe *et al.*, 2016; Papatryphon *et al.*, 2004; Poore and Nemecek, 2018) make the assessment of insects produced on conventional feeds somewhat easier and flexible in terms of selection of LCIA methods and indicators. However, the reliability of data and previous studies should be thoroughly analysed for the consistency and representability.

Additionally, the boundaries for insect feed production sometimes include side-streams and secondary products from food processing or agriculture (Bava *et al.*, 2019; Bosch *et al.*, 2019; Ites *et al.*, 2020; Maiolo *et al.*, 2020; Smetana *et al.*, 2016). It is envisioned that insect production in the future will even stronger rely on side-streams and secondary products from food processing or agriculture due to its potential for a constant supply (Smetana *et al.*, 2019b). In such cases the upstream production impacts should be allocated to the relevant by-product following physical or economic criteria (Ardente and Cellura, 2012). Formulations of feed for insects from food products at retail or consumer stages (wastes) should follow a dual approach – it should include all the impacts of upstream production and avoided waste treatment (Mondello *et al.*, 2017; Salomone *et al.*, 2017; Smetana *et al.*, 2016).

Depending on the type of feed the LCA of this stage should rely on careful allocation or system expansion which to a great degree would determine the overall impact of insect production and further use of insect for food or feed (Smetana *et al.*, 2019b; Van Zanten *et al.*, 2018). The importance of this stage is connected also with limited availability of data on the processing characteristics and allocated value and impacts to the by-products. Published studies rely mostly on attributional approaches and economic or nutritional allocation (Table 1) and rarely on system expansion and consequences on the market (Smetana *et al.*, 2019b; Van Zanten *et al.*, 2018).

Feed transportation and storage

Insect feed transportation is performed by usual means of dry and liquid feed transport relying on road infrastructure (trucks, lorries, and tractors). Most studies rely on rather short distances for the feed delivery in the scope of 100-300 km, which is justified due to the economic feasibility and availability of local suppliers (Bava *et al.*, 2019; Maiolo *et al.*, 2020; Smetana *et al.*, 2016), unless feed contains soy, grown overseas (Halloran *et al.*, 2017). It should be considered that in most cases transportation (along the whole production chain) contributes only a small share to the overall environmental impact, amounting to 2-6% of impact depending on the category (largest impacts in global warming potential, resource depletion and ozone depletion) and modelled scenario (distance, means of transportation). The share of feed transportation impact is increased in case of insect production on wastes – it can be responsible for up to 18% of GWP (Salomone *et al.*, 2017), however no increase is observed in absolute values. Most of the studies either model the delivery of feed or rely on existing databases for the analysis. Data availability is not a limiting factor for this assessment module.

Secondary feed production and processing

Feed and food processing stages are currently considered as very challenging to model due to the limitations in data availability, huge diversity of potential alternatives and diversity of application scales (Ites *et al.*, 2020; Smetana *et al.*, 2016, 2019b). Feed is mostly delivered to insects in dried or high-moisture forms. Dried feeds are supplied to mealworms, crickets, and grasshoppers, while moisturised feeds are prepared for larvae of flies. Dried feeds, sources from grains, require minimal processing which might consist of mixing, cutting and grinding. In some cases, additional sources of moisture like vegetables are supplied alongside the dried feeds (Halloran *et al.*, 2017; Oonincx and De Boer, 2012). Moisturised feeds, on the other hand, might be derived from wetting dried feeds or they might be delivered in moist form from the supplier (wet mills, breweries, farms in case of manure, etc.). Similar to transportation, the impact of the feed processing stage is minimal and that is why in most cases feed processing is considered in rather aggregated form. Recently investigated options for insect feed pre-treatment (Isibika *et al.*, 2019; Ravindran and Jaiswal, 2019) are not included in the examined LCA studies.

Insect farming

Insect farming together with insect biomass fractionation (separation of insect biomass into fractions including drying) are responsible for a considerable portion of environmental impact, which is reflected in the range of 15-70% depending on impact category and level of processing in LCA studies (Bava *et al.*, 2019; Halloran *et al.*, 2017; Maiolo *et al.*, 2020; Smetana *et al.*, 2016, 2019b; Thévenot *et al.*, 2018). Thus, high importance in the impact contribution is highlighted for energy consumption. Literature indicated that 18.4-37.6% of energy is used for insect farming, while the bigger part of cumulative energy demand (58.7-79.8%) is allocated to the production of main consumables (Maiolo *et al.*, 2020). Inclusion of processing in the farming stage rises the impact to 37-55% of overall energy consumed (Smetana *et al.*, 2019b). Separation of insect rearing and further biomass processing, depending on scenarios, results consumption of 50% of electricity used for insect rearing (Thévenot *et al.*, 2018). Insect biomass drying is responsible

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for a fraction of 7-45% of direct electricity used (Bava *et al.*, 2019) and fat separation for around 50% of electricity used or 48-55% of cumulative energy demand (Thévenot *et al.*, 2018; Van Zanten *et al.*, 2015). Heating with the gas could add another 22% to the energy use impact (Van Zanten *et al.*, 2015). Electricity and natural gas use at insect farming then are responsible for 51% of total GWP (Van Zanten *et al.*, 2015). Similarly, Suckling *et al.* (2020) indicates the impacts of rearing on global warming to be responsible for 59% of GWP with third part being allocated to heating. Therefore, the detailed analysis of insect farming and identification of improvement potential could play an important role. Direct metabolic emissions are indicated as neglectable (Ermolaev *et al.*, 2019; Mertenat *et al.*, 2019; Parodi *et al.*, 2020).

Insect cultivation

The properties of feed for insects to a great degree define the environmental performance of the whole production system due to three main characteristics: (1) type of insect feed and associated upstream impacts; (2) feed conversion ratio; and (3) residual biomass management (Table 2). LCA of insect production therefore should thoroughly, holistically and in a detail define these characteristics. Feed type and composition play an important role due to the upstream environmental impact associated with production (Halloran *et al.*, 2017; Oonincx and De Boer, 2012; Thévenot *et al.*, 2018; Van Zanten *et al.*, 2015) or due to the amount of avoided impacts in case of waste treatment substitution (Bava *et al.*, 2019; Mertenat *et al.*, 2019; Salomone *et al.*, 2017; Smetana, 2020). Feed production for insects is responsible for a vast impact of insect production: 20-99% of contribution depending on the impact category (Bava *et al.*, 2019; Halloran *et al.*, 2017; Maiolo *et al.*, 2020; Oonincx and De Boer, 2012; Roffeis *et al.*, 2017, 2020; Smetana *et al.*, 2016, 2019b). Insect cultivation could be responsible for 95% of water resource depletion, 70% of land use, 45% of ozone depletion, 45% of freshwater eutrophication (Suckling *et al.*, 2020).

Furthermore, feed conversion (or bioconversion) defines the efficiency of insect feeding and growing, as the lower the feed conversion ratio (FCR) over specific timeframe the higher the performance of the production system and lower the environmental impact as long as the similar impacting feeds are considered. FCR, however, is not always transparently reflected in the studies. Different approaches include 'wet to wet' (Halloran *et al.*, 2017; Maiolo *et al.*, 2020; Oonincx and De Boer, 2012; Van Zanten *et al.*, 2015), 'wet to dry' (Roffeis *et al.*, 2017, 2020; Salomone *et al.*, 2017), 'dry to dry' (Bava *et al.*, 2019; Smetana *et al.*, 2019b) basis. Moreover, in some cases only 'ingested' feed was considered in the analysis of FCR (Bava *et al.*, 2019; Halloran *et al.*, 2017; Oonincx and De Boer, 2012; Thévenot *et al.*, 2018), while other studies include 'non-ingested' feed in the calculations, which jointly with the other factors could result in higher FCR. However, several of the reviewed studies indicate the generation of residual biomass, with further management through by-product allocation (Roffeis *et al.*, 2017, 2020; Smetana *et al.*, 2016, 2019b) or conventional waste treatment through anaerobic digestion (Smetana *et al.*, 2016). Modelling of residual biomass management would therefore include the allocation of part of the total environmental burden to a by-product (lowering the impact of the main insect biomass product) or it will add environmental burden to main product associated with waste treatment.

Energy use, GWP, and water use are the main contributors to the environmental impact of insect cultivation. While data is available from different studies, it is still fragmented, not always transparent and, in many cases, aggregated (thus difficult to reproduce). Data for the insect growing stage are also limited. Some studies indicate on the resources used for insect rearing (Thévenot *et al.*, 2018), climate system (Bava *et al.*, 2019; Smetana *et al.*, 2019b), and insect feeding (Smetana *et al.*, 2016). However, a complete detailed picture is not presented.

Reproduction

Insect reproduction is included in the production chain as a circulating component, separating a minor part of the adult population for mating and egg laying (Dossey *et al.*, 2016; Ites *et al.*, 2020; Salomone *et al.*, 2017; Thévenot *et al.*, 2018). Most of the studies analyse the larval stage of insect production, as this stage is the most nutritionally relevant for species from *Diptera* and *Coleoptera* orders (Table 3). For the *Orthoptera* order, on the other hand, the adult life stage is relevant, therefore, LCA of such insect production concentrated on adult stages.

Insect reproduction is usually separated from main feeding and growing into a separate facility. Sometimes reproducing population gets another type of treatment, which ensures better reproduction performance. Despite a special treatment, reproduction module is responsible for a minor impact in the scope of 2-8% (Salomone *et al.*, 2017; Smetana *et al.*, 2019b; Van Zanten *et al.*, 2015), which is often excluded from the boundaries of LCA studies (Ites *et al.*, 2020; Smetana *et al.*, 2016) or combined with main production (Bava *et al.*, 2019; Salomone *et al.*, 2017; Smetana *et al.*, 2019b). In some cases the impact of reproduction can reach up to 10% (Thévenot *et al.*, 2018). The highest impacts are associated with energy use and global warming potential. Similar to insect growing and feeding, only limited data is available for a transparent analysis.

Table 2. Insect feeding characteristics.[1]

Study	Feed type and components	Feed conversion	Residual biomass amount	Residual biomass management modelling
Ooninсx and De Boer, 2012	Proprietary feed: fresh carrots, mixed grains supplemented with beer yeast	2.2 kg feed/ kg live weight	Not provided	Larvae manure as output, 100% allocation of impacts to insect output
Smetana *et al.*, 2015	Used data from Oonincx and De Boer (2012)			
Roffeis *et al.*, 2015	Pig manure (fresh/dewatered)	2.8-7.4 kg substrate (DM) for 0.32-0.35 kg insects (DM)	1.8-6.4 kg (DM)	Packed residue substrate as one of outputs of system, all impacts allocated to FU manure reduction, none to insect output
Van Zanten *et al.*, 2015	Mixed: food waste, laying hen manure, premix (vitamins and minerals)	4 kg substrate yield 1 kg fresh larvae	Not provided	Manure considered as fertiliser in consequential assessment, economic allocation in attributional part
Komakech *et al.*, 2015	Organic waste and animal manure (theoretical)	Not provided	Not provided	Insect frass is a soil improver/fertiliser, all impacts allocated to use of compost output; system expansion for (1) avoided fertiliser production and (2) avoided production of silver cyprinid for application in animal feed (fly larvae assumed to substitute silver cyprinid)
Smetana *et al.*, 2016	Grains: rye meal, wheat bran	22-109 kg / 1 kg of meal and 0.9 kg lipids	Not provided	Insect frass is a fertiliser or treated as waste, mass and economic allocation
	Chicken manure			
	Cattle manure			
	Food processing by-product: beet pulp			
	Food processing by-product: distiller's dried grains with solubles (DDGS)			
	Municipal organic waste			
Salomone *et al.*, 2017	Food waste, average composition: 65% vegetal, 5% meat/fish, 25% bread/pasta/rice, 5% other	10 t feed for 0.3 t dried larvae	10 t feed for 3.346 t manure	Larvae frass is a fertiliser, for FU1: system expansion - avoided compost production; for FU2, 3: impact of bioconversion fully allocated to insect output (economic allocation, lower compost price)
Halloran *et al.*, 2017	Proprietary broiler feed: fish meal, soybean meal, grain maize, rice bran, palm oil, calcium carbonate, salt (optionally pumpkin)	1.47-2.5 kg feed ingested for 1 kg insects (WM)	Quantity of manure 72-85% of mass of harvested crickets (calculated)	Insect frass is a fertiliser, system expansion - avoided fertiliser production (amount based on full substitution of N, P, K in residual biomass)
Joensuu and Silvenius, 2017	Used data from Oonincx and De Boer (2012) and Oonincx *et al.* (2015)			
Thévenot *et al.*, 2018	Composite feed: cereal flours and meals, wheat bran, beat pulp	1.98 kg feed ingested for 1 kg larvae (WM)	3.85 kg per kg of meal	Insect frass is a fertiliser, all impact allocated to insect outputs; impacts from fertiliser out of scope

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Table 2. Continued.

Study	Feed type and components	Feed conversion	Residual biomass amount	Residual biomass management modelling
Bava *et al.*, 2019	Control hen diet	4.22 kg DM ingested feed for 1 kg DM larvae	3.056 kg DM residual feed and manure	Insect frass is a fertiliser, system expansion - avoided fertiliser production
	Food processing by-product: okara	2.80 kg DM ingested feed for 1 kg DM larvae	0.583 kg DM residual feed and manure	
	Food processing by-product: maize distiller's grains	2.81 kg DM ingested feed for 1 kg DM larvae	2.757 kg DM residual feed and manure	
	Food processing by-product: wet brewer's spent grains	3.30 kg DM ingested feed for 1 kg DM larvae	0.850 kg DM residual feed and manure	
Mertenat *et al.*, 2019	Organic waste: segregated household biowaste	Not provided	Not provided	Residues composted and sold on market; production of compost is part of functional unit; impacts allocated to waste treatment and compost production; system expansion to substitute larvae meal: avoided fishmeal production
Roffeis *et al.*, 2017, 2020	Chicken manure	40 kg for 1 kg dried larvae	28 kg residue	Insect frass is a fertiliser, FU1 system performance no allocation; FU2 economic allocation
	Sheep manure and fresh ruminant blood	37 kg for 1 kg dried larvae	16 kg residue	
	Chicken manure and fresh brewery waste	15.7 kg feed yielded 1 kg dried larvae	7.1 kg residue	
Smetana *et al.*, 2019b	Side streams from milling, alcohol production, breweries	32.24 kg feed yielded 1.44 kg fresh puree, 1 kg meal, 0.34 kg lipids, 3.82 kg frass		Insect frass is a fertiliser; economic allocation for outputs (3.08:1 fresh insects:fertiliser)
Ites *et al.*, 2020	Expired food products: organic waste	10 kg for 1 ton feed (WM)	60 kg for 1 ton feed	Insect frass is a fertiliser (hypothetic economic allocation)
	Food processing by-product: potato peels	0.32 t insect for 1 ton feed (WM)	0.11 ton for 1 ton feed	
	Food processing by-product: brewery grains	28.4 kg for 1 ton feed (WM)	0.12 ton for 1 ton feed	
Maiolo *et al.*, 2020	Cereal by-products/grains	9.3 t of feeding substrate for 1.3 t larvae (live weight); 6 t of substrate for 1 t of meal	8,017 kg residue substrate and dead adult flies per 1000 kg insect meal	Insect frass is a fertiliser, economic allocation (low value to insect frass)
Suckling *et al.*, 2020	Composite feed: wheat, meals, fats and oils, additives; plus peat	113.3 t feeding substrate (peat 17.46 t) for 12.5 t crickets (live weight)	107.5 t frass (WM); 98.5 t (DM)	Insect frass is a fertiliser, mass allocation; avoided production of fertiliser

[1] DM = dry matter basis; FU = functional unit; WM = wet matter basis.

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Table 3. Insects investigated in life cycle assessment studies.

Study	Species	Family	Order	Life stage studied
Bava *et al.*, 2019; Bosch *et al.*, 2019; Ites *et al.*, 2020; Komakech *et al.*, 2015; Maiolo *et al.*, 2020; Roffeis *et al.*, 2017, 2020; Salomone *et al.*, 2017; Smetana *et al.*, 2016, 2020a	*Hermetia illucens*	Stratiomyidae	Diptera	larval/pre-pupae
Mertenat *et al.*, 2019; Smetana *et al.*, 2019b	*Hermetia illucens*	Stratiomyidae	Diptera	larval/adult
Ites *et al.*, 2020; Joensuu and Silvenius, 2017; Oonincx and De Boer, 2012; Smetana *et al.*, 2015, 2020a	*Tenebrio molitor*	Tenebrionidae	Coleoptera	larval
Thévenot *et al.*, 2018	*Tenebrio molitor*	Tenebrionidae	Coleoptera	larval/pre-pupal
Oonincx and De Boer, 2012	*Zophobas morio*	Tenebrionidae	Coleoptera	larval
Van Zanten *et al.*, 2015	*Musca domestica*	Muscidae	Diptera	larval
Roffeis *et al.*, 2015, 2017, 2020	*Musca domestica*	Muscidae	Diptera	larval/adult
Ulmer *et al.*, 2020	*Apis mellifera*	Apidae	Hymenoptera	pupa
Halloran *et al.*, 2017; Suckling *et al.*, 2020	*Gryllus bimaculatus*	Gryllidae	Orthoptera	adult
Halloran *et al.*, 2017	*Acheta domesticus*	Gryllidae	Orthoptera	adult
Suckling *et al.*, 2020	*Gryllus sigillatus*	Gryllidae	Orthoptera	adult

Insect products

Insect production can result in a few potential products in the range from fresh live insects to fractionated and incorporated intermediates. All these products are a subject for a proper storage to assure their longer preservation and safety of further product development and distribution. These steps are rarely described in LCA studies, with a few exceptions (Smetana *et al.*, 2015, 2020a).

Primary processing

When insects reach the desired parameters in terms of size, age and composition they are processed in two stages. Primary processing aims to clean insect biomass and eliminate microbial load using operations like sieving, separation, blanching, decontamination or freezing while secondary processing targets improved properties of insect derived components through operations like milling, fractionation via centrifugation, drying and fat separation. The differences in processing result in a variation of end products sold to business or final consumers: whole live insects, whole fresh/frozen insects, fresh insect puree, dried whole larvae, defatted meal, insect oil, intermediate products containing insect components. Variations in processing depths allow to group the scope of most LCA studies into three main system boundaries: (1) cradle-to-farm gate; (2) cradle-to-processing gate; and (3) cradle-to-plate (Figure 1). For the first system boundaries (1) the resulting products are alive insects, suitable mostly for feed application (Bosch *et al.*, 2019; Komakech *et al.*, 2015; Oonincx and De Boer, 2012; Suckling *et al.*, 2020). Application of alive larvae for direct food consumption is doubtful as currently there are no companies producing live larvae for direct human consumption. Whole larvae and adult insects, decontaminated and sometimes dried (2), on the other hand, are indicated to be applied directly for food and feed (Bava *et al.*, 2019; Halloran *et al.*, 2017; Ites *et al.*, 2020; Mertenat *et al.*, 2019; Roffeis *et al.*, 2015; Salomone *et al.*, 2017). Most studies, however, are concentrated on the assessment of fractionated or incorporated insect products in cradle-to-processing gate boundaries (Maiolo *et al.*, 2020; Smetana *et al.*, 2016, 2019b, 2020b; Thévenot *et al.*, 2018; Ulmer *et al.*, 2020; Van Zanten *et al.*, 2015).

Storage and packaging

Storage of insect products is of utmost importance for fresh (high-moisture) products like live, fresh-frozen insects and insect biomass incorporated in high-moisture products (Smetana *et al.*, 2015, 2016; Ulmer *et al.*, 2020). High water activity of such products usually requires low temperatures: cooled conditions for live insects and freezing for other products. Energy consumption in this case might be a considerable factor influencing the environmental impact of the insect product. Therefore, cooling and freezing storage periods should be limited to reduce the environmental impact. Insect based food and feed products of longer shelf-life nevertheless require specific storage conditions like dry rooms with climate-controlled conditions. Packaging is rarely mentioned in insect LCA studies and assumed to be comparable to the similar products in feed and food industry. Therefore, it can play a similar role of having a diverse ratio of impacts depending on the size of the product, weight of packaging, and material composition (Vignali, 2016).

Fractionation

Secondary processing of insect biomass relates to fractionation (separation) into a few fractions: water, lipid and protein. The purity of fractionation depends on the

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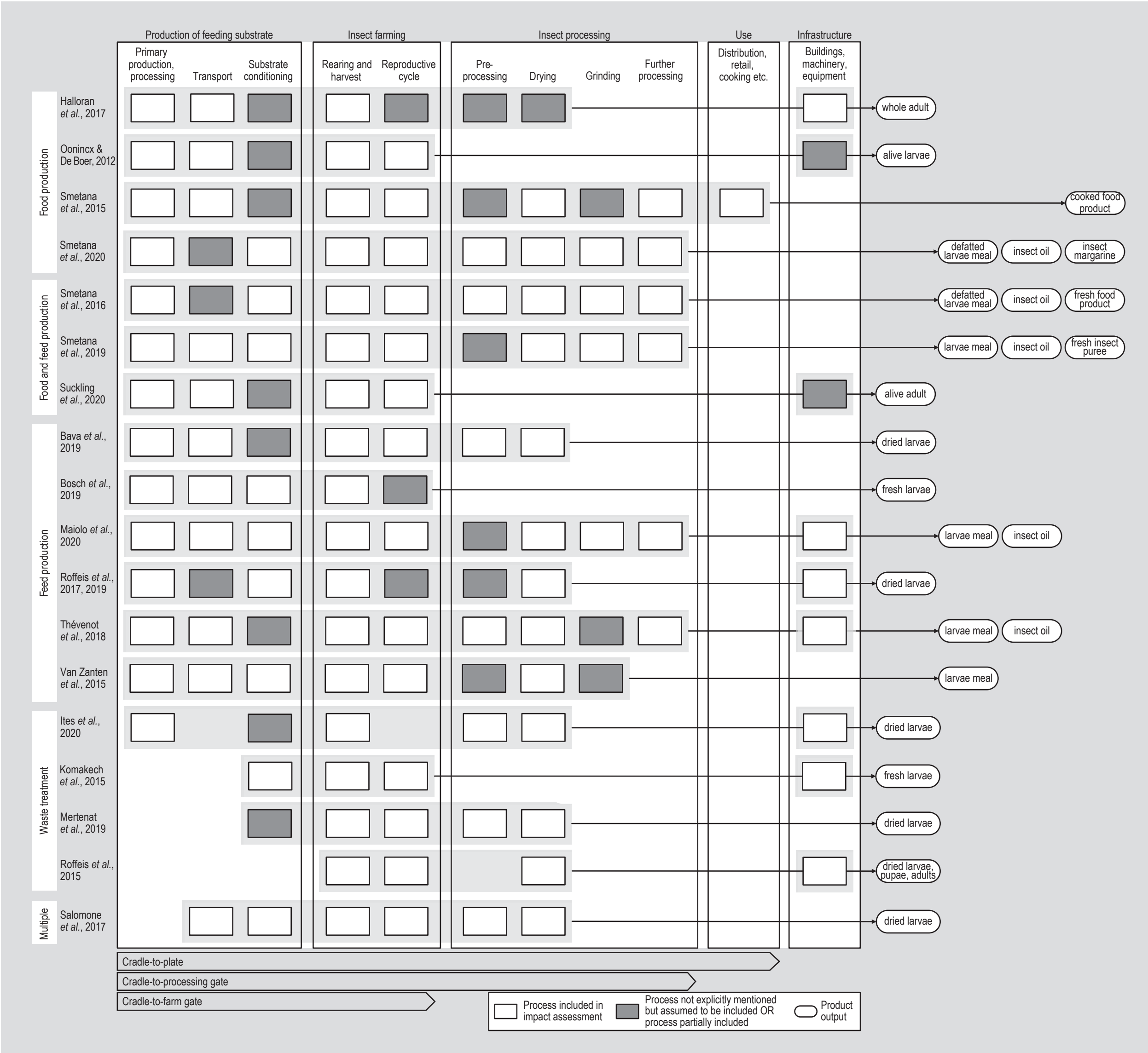

Figure 1. Graphical mapping of insect production chains.

technology applied. Insect drying, relying on different technologies (heat drying, solar drying, freeze-drying) is indicated in a few studies as one of the most common processing techniques used (Bava *et al.*, 2019; Ites *et al.*, 2020; Mertenat *et al.*, 2019; Roffeis *et al.*, 2017, 2020; Salomone *et al.*, 2017; Smetana *et al.*, 2019b). It can have a relatively high energy demand and could results in high associated environmental impacts. In some cases, the heat used for insect production could be sourced as a by-product from other industries and have low environmental impacts (Joensuu and Silvenius, 2017). In other cases, when a high quality of insect biomass should be assured for food applications, e.g. drying is relying on lyophilisation technologies (freeze-drying of whole larvae (Bava *et al.*, 2019; Lenaerts *et al.*, 2018), which is associated with high energy expenses and relatively high impacts.

Further fractionation techniques include separation of water, lipid and protein fractions from fresh and dry biomass by centrifugation, cold or hot pressing (Alles *et al.*, 2020; Smetana *et al.*, 2019b, 2020a) and in some cases by supercritical liquid extraction (Purschke *et al.*, 2017). Emerging food processing technologies (such as pulsed electric fields) are also finding its niche in improvement of insect biomass fractionation (Alles *et al.*, 2020; Shorstkii *et al.*, 2020; Smetana *et al.*, 2020b). With such developments the dependence on energy is reduced as well as the relative environmental impact.

Integration (product development)

Further product development is associated with use of the concentrated protein fraction (insect flour, insect meal or defatted protein concentrate) and of insect lipids (fats and

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oils) as a part of a more complex matrix. The applications of both protein and lipid fractions are associated with both feed and pet-food (Gasco *et al.*, 2020; Surendra *et al.*, 2016; Zorrilla and Robin, 2019) as well as food applications (Smetana *et al.*, 2015, 2016, 2018b, 2020a; Tzompa-Sosa *et al.*, 2019). Protein fractions are incorporated into new products through mixing and baking (González *et al.*, 2019; Roncolini *et al.*, 2020); extrusion cooking and pelletising or high-moisture extrusion for meat substitutes production (Smetana *et al.*, 2018b, 2019a; Ulmer *et al.*, 2020). Diverse application possibilities result in several tested and marketed products: pelleted feeds, bars, pasta, spreads, etc. Mixing of fresh or dried insect biomass with plant material results in hybrid products, which potentially can have a lower environmental impact. However, high levels of processing (in case of isolates application) could increase the impacts of the final product.

Lipid fractions are either used as an additive for animal feed (Gasco *et al.*, 2019), for baking purposes (Delicato *et al.*, 2020; Tzompa-Sosa *et al.*, 2019) or as a part of complex fat products such as spreads and margarines (Smetana *et al.*, 2020a). There are only a couple studies, which performed LCA research in the scope of cradle-to-product application boundaries (Figure 1), even though cooking of the product at consumer stage may pose considerable environmental impacts associated with long preservation, excessive wasting and high energy use at inefficient cooking practices (Smetana *et al.*, 2015). Despite multiple challenges associated with suboptimal production chains, insect products are often assessed as having a similar or lower environmental impact compared to conventional food and feed products (Bava *et al.*, 2019; Halloran *et al.*, 2017; Oonincx and De Boer, 2012; Salomone *et al.*, 2017; Smetana *et al.*, 2016, 2020a).

5. Conceptualisation of a modular assessment framework for insect production

Despite quite a few studies presenting LCA results, there is an evident lack of systemised information, inhibiting comparisons with other insect products and production chains or with conventional products. Insect production LCA studies are often performed on lab-scale and small pilot-scale level, which does not allow for a direct result transfer to industrial scales (Table 4). Upscaling of insect production will likely decrease the environmental impact of insect product (Heckmann *et al.*, 2019; Smetana *et al.*, 2018a, 2019b).

Climate change is one of the most popular categories of assessment in the studies. Use of a control diet (standard,

Table 4. Characterisation of insect life cycle assessment studies according the production scale and environmental impacts.[1]

Studies	Unit	Scale of production/ assessment	Impacts		
			Control diet	Food processing by-product/food waste	Manure diet
Bava *et al.*, 2019	1 kg DM whole larvae	Lab: 1000 larvae per batch	CC: 5.76 LU1: 94.7 WRD: 1.26	CC: 0.7-2.0 LU1: 1.3-4.9 WRD: 0.8-1.1	n/a
Bosch *et al.*, 2019	1 kg of protein	Lab: 100-1000 larvae per batch	GWP: 4-7 EU: 159-202 LU: 11-93	GWP: 1-5 EU: 18-77 LU: 0-1	GWP: 1-7 EU: 0-22 LU: 0
Halloran *et al.*, 2017	FU1: 1 kg edible WW; FU2: 1 kg of protein in edible	Pilot: 36.7 tons of insects annually	FU 1 CC: 2.3-2.6 WRD: 0.42 FU 2 CC: 3.9-4.4 WRD: 0.71	n/a	n/a
Joensuu and Silvenius, 2017	FU1: 1 kg WM whole larvae; FU2: 1 kg of protein	Based on: Oonincx *et al.*, 2015; Oonincx and de Boer, 2012	FU1: GWP2: 3.1 FU2: GWP2: 23-27	FU1: GWP2: 3.1	n/a
Ites *et al.*, 2020	1 kg DM whole larvae*	Pilot mobile: 12.7-64 tons of insects annually	n/a	GWP1: -6.42 to 2.0 NRE: -108 to 8.9 LO: -16.8 to -0.006	n/a

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Table 4. Continued.

Studies	Unit	Scale of production/ assessment	Impacts		
			Control diet	Food processing by-product/food waste	Manure diet
Komakech *et al.*, 2015	1 kg DM whole larvae*	Industrial hypothetical: 426 tons of insects annually	n/a	GWP2: 0.29 EU1: 0.36	n/a
Oonincx and De Boer, 2012	1 kg WM whole larvae	Pilot: 83 tons of fresh insects annually	GWP2: 2.7 EU1: 33.7 LU: 3.6	n/a	n/a
Roffeis *et al.*, 2015	1 kg DM whole larvae*	Pilot: 1 tonne manure per week	n/a	n/a	FD: 5.9-9.7; ALO: 4.4-7.7; WD: 113.9-187.6
Roffeis *et al.*, 2017, 2020	1 kg DM whole larvae	Pilot: 3.5-4.4 tons DM larvae annually	n/a	GWP3: 4.5-12; FD: 0.96-1.5 ALO: 5.5-61 WD: 8.5-11	
Salomone *et al.*, 2017	1 kg DM whole larvae*	Pilot industrial: 110-329 tons DM larvae annually	n/a	GWP4: 1.0; EU2: 7.2 LU3: 0.022	n/a
Smetana *et al.*, 2016	1 kg DM dried defatted powder	Pilot industrial: 50 tons insect flour	GWP1,3: 1.36-15.1 NRE: 21.2-99.6 (A)LO: 0.0032-7.03		
Smetana *et al.*, 2019b	1 kg DM dried meal	Industrial: more than 1000 tons DM larvae annually	n/a	GWP1: 5.3 NRE: 84.2 LO: 1.9 WU: 2.8	n/a
Smetana *et al.*, 2020a	1 kg DM margarine (insect lipids)	Based on: Smetana *et al.*, 2019b; Thévenot *et al.*, 2018	n/a	GWP1:2.4-4.1 NRE: 16.4-54 LO: 2.4-3.7	n/a
Thévenot *et al.*, 2018	1 kg WM whole larvae	Pilot: 17 t WM larvae annually	n/a	EU2: 24.3 CC1: 0.99 LU3: 1.6	n/a
Ulmer *et al.*, 2020	1 kg of edible protein	Lab: 40 kg WM from 12 colonies annually	GWP1: 15-29 NRE: 248-425 LO: 1.1-17	n/a	n/a
Van Zanten *et al.*, 2015	1 kg DM dried meal	Pilot industrial?	n/a	GWP2: 0.77 EU1: 9.3 LU2: 0.032	
Suckling *et al.*, 2020	1 kg WM whole larvae	Pilot: 12.5 t WM insects annually	CC: 21.1 LU1: 157 WRD: 0.82	n/a	

[1] ALO = agricultural land occupation in m^2yr (ReCiPe); CC1 = climate change in kg CO_2 eq. (CML2); CC = climate change in kg CO_2 eq. (ILCD 2011); DM = dry matter basis; EU = energy use in MJ (not specified method); EU1 = energy use in MJ (separate indicator); EU2 = energy use in MJ (CML 2); FD = fossil depletion kg oil eq. (ReCiPe); GWP = global warming potential in kg CO_2 eq. (not specified method); GWP1 = global warming potential in kg CO_2 eq. (IMPACT2002+); GWP2 = global warming potential 100 years in kg CO_2 eq. (separate indicator); GWP3 = global warming potential in kg CO_2 eq. (ReCiPe); GWP4 = global warming potential in kg CO_2 eq. (IPCC 2007); LO = land occupation m^2 org arable (IMPACT2002+); LU = land use m^2 (not specified method); LU1 = land use in kg C deficit (ILCD 2011); LU2 = land use in m^2, separate indicator; LU3 = land use in m^2a (CML 2); NRE = non-renewable energy consumption in MJ primary (IMPACT2002+); WD = water depletion in m^3 (ReCiPe); WM = wet matter basis; WRD = water resource depletion in m^3 water eq. (ILCD 2011); WU = water use in L deprived (IMPACT World+); * = recalculated for 1 kg DM of whole larvae.

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based on commercial or proprietary feed) is associated in with 2.3-3.1 kg CO_2 eq. per kg of fresh insects produced (Halloran *et al.*, 2017; Joensuu and Silvenius, 2017; Oonincx and De Boer, 2012). It corresponds well to the results presented for 1 kg of dried larvae: 5.76 kg CO_2 eq. (Bava *et al.*, 2019) and for 1 kg of protein: 3.9-7 kg CO_2 eq. (Bosch *et al.*, 2019; Halloran *et al.*, 2017). At the same time, some authors highlight carbon footprint as high as 21.1 kg CO_2 eq. per kg of fresh larvae (Suckling *et al.*, 2020) or in the range of 15-29 kg CO_2 eq. per kg of protein (Ulmer *et al.*, 2020). The high impact in last studies is explained by inclusion of frass application to the field as emission factor (Suckling *et al.*, 2020) or by the analysis of a very different production system with low technology readiness level (Ulmer *et al.*, 2020).

Global warming potential impacts of insect production based on food processing by-products (food waste) can vary in a wide range from positive for the environment -6.42 to 5.3 kg CO_2 eq. for all the FUs (Bava *et al.*, 2019; Bosch *et al.*, 2019; Ites *et al.*, 2020; Joensuu and Silvenius, 2017; Komakech *et al.*, 2015; Salomone *et al.*, 2017; Smetana *et al.*, 2019b; Thévenot *et al.*, 2018; Van Zanten *et al.*, 2015). The only study differentiated form the majority indicates somewhat higher impacts of 4.5-12 kg CO_2 eq. per 1 kg DM (Roffeis *et al.*, 2017, 2020). Application of manure as feed for insects could have a great potential for the environmental improvement (Smetana *et al.*, 2016). However, reviewed studies indicated considerable impacts on the environment from 0.77-12 kg CO_2 eq. per 1 kg of dried insects (Roffeis *et al.*, 2017, 2020) to 1-7 kg CO_2 eq. per 1 kg of proteins (Bosch *et al.*, 2019).

Water footprint is assessed only in a few studies, indicating that with control diet 1 kg of fresh insects result in 0.42-0.82 m^3 of water depleted (Halloran *et al.*, 2017; Suckling *et al.*, 2020). Similar impact is indicated for the protein-based unit: 0.71 m^3 (Halloran *et al.*, 2017). Calculation of the results per dry matter content results in higher impacts 1.26 m^3 (Bava *et al.*, 2019).

Production of insects on by-products (food waste) results in the contradictory amounts of water depleted from low 0.8-1.1 m^3 per kg of dry matter content (Bava *et al.*, 2019) to high 8.5-11 m^3 per kg of fresh insects produced (Roffeis *et al.*, 2017, 2020). Water footprint of insects produced on manure is also not indicative with ranges from low: 8.5-11 m^3 per 1 kg of insect on dry matter basis (Roffeis *et al.*, 2017, 2020) to very high: 113.9-187.6 m^3 (Roffeis *et al.*, 2015). There is a lack of studies indicating the water footprint of insects grown on food waste and manure. Higher impacts might be explained by more regionalised approach taken in the studies (Roffeis *et al.*, 2015, 2017, 2020).

Application of conventional diet results in quite high energy use impacts: 33.7 MJ per kg of fresh insects produced (Oonincx and De Boer, 2012); 159-425 MJ for 1 kg of proteins (Bosch *et al.*, 2019; Ulmer *et al.*, 2020). Energy use for insect production in case they are grown on by-products and food waste according to the reviewed studies is very diverse and ranges from rather positive -108 to 8.9 MJ per 1 kg of insect biomass on dry matter basis (Ites *et al.*, 2020; Komakech *et al.*, 2015; Salomone *et al.*, 2017) to high impacts of 24.3 MJ per kg of fresh insects produced (Thévenot *et al.*, 2018) or 18-77 MJ per 1 kg protein (Bosch *et al.*, 2019). Variations in the impacts can be explained by the differences in the modelling approaches (consideration of raw materials as by-products or wastes).

Use of energy for insect production on manure highlighted in a few studies, has moderate ranges: from 9.3-62.8 MJ per 1 kg of dry insects (Roffeis *et al.*, 2017, 2020; Van Zanten *et al.*, 2015) and 0-22 MJ per 1 kg of proteins (Bosch *et al.*, 2019). However, a single study indicated a huge potential impact in energy use: 247-406 MJ per 1 kg of dry larvae (Roffeis *et al.*, 2015). The explanation might lay in the biological or geographical variations applied in the study.

Assessment of land use impact in the studies dealing with conventional diet is not straightforward. While production of fresh insects could result in 3.6 m^2 per kg of fresh insects produced (Oonincx and de Boer, 2012), land use impact calculated in other studies is much higher: 94.7 m^2 per 1 kg of insects dry matter basis (Bava *et al.*, 2019), 1.1-93 m^2 per 1 kg of proteins (Bosch *et al.*, 2019; Ulmer *et al.*, 2020). Land use impacts of insect production of by-products are indicated as low: 1.6 m^2 per kg of fresh insects produced (Thévenot *et al.*, 2018); -16.8 to 4.9 m^2 per 1 kg of insect on a dry matter basis (Bava *et al.*, 2019; Ites *et al.*, 2020; Salomone *et al.*, 2017; Smetana *et al.*, 2019b; Van Zanten *et al.*, 2015) and 0-1 m^2 per 1 kg proteins (Bosch *et al.*, 2019). Studies of Roffeis *et al.* (2017, 2020) highlight the possibility of higher land use impact: 5.5-61 m^2 per 1 kg on dry matter basis. Regionality might play here a high role as well. Land use impacts were low in studies dealing with manure treatment: 0.032 -7.7 m^2 per 1 kg of insect on dry matter basis (Roffeis *et al.*, 2015; Van Zanten *et al.*, 2015) and even neutral in some cases: 0 m^2 per 1 kg of proteins (Bosch *et al.*, 2019). And again, there was one outline study highlighting rather high impact associated with land use: 5.5-61 m^2 per 1 kg of insects produced (Roffeis *et al.*, 2015) potentially due to its concentration on a specific regional basis.

The variations in insect species, units of measurement, assessed scale of production and feeding diets do not allow for a straightforward evaluation of different production pathways (Table 4). However, the overall tendency indicates that the use of food processing by-products, wastes or manure for insect feeding can reduce the environmental impact of insect products (Bosch *et al.*, 2019; Ites *et al.*, 2020; Komakech *et al.*, 2015; Roffeis *et al.*, 2017, 2020;

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Salomone *et al.*, 2017; Smetana *et al.*, 2016; Van Zanten *et al.*, 2015). The impact of insect production furthermore can be reduced through the application of alternative energy sources (Smetana *et al.*, 2016, 2019b), use of insect for additional ecosystem services tasks (pollination, biotransformation) (Ulmer *et al.*, 2020), application of more efficient processing chains and use of passive heating and cooling methods or application of live insect with minimal processing.

The complexity of insect production chains does not allow for simple and straightforward answers about the environmental impact of insect-based products. The impact depends on the type of insect, compositions of the diet, optimisation of growing conditions, level of processing, type of distribution, etc. In order to analyse the relative efficiency, economic feasibility and environmental impact of insect production chains it is necessary to rely on a systematic holistic approach, which should include modularisation of insect production stages and their analysis on a standardised scale.

Based on the reviewed publications and available results of LCA studies we propose a modular framework, which should improve the performance of future LCA studies. It consists of 3 main components. The first component includes determination of system boundaries of insect production chains and relevant comparable studies via graphical mapping (Figure 1). For a comparative analysis insect production chains should be divided conceptually into five main groups representing: (1) the production of feeding substrate (as indicated to be of highest importance for the environmental impact); (2) insect farming; (3) processing; (4) overall infrastructure; and (5) application of insect product. These five groups combine represent the variability in the scope and boundaries of LCA – cradle-to-gate, cradle-to-plate, etc. (Figure 1), which leads to the identification of the type of insect production chain. Further LCA analysis should include more detailed modules of insect production. For example, insect farming could be further differentiated into modules of reproduction, fattening, supporting services (washing), and pre-processing (if located in the same facility). Thus, the characterisation of substrate production should include primary production or processing, transportation and on-site substrate conditioning. Insect farming consists of two main modules: rearing-harvesting and reproduction. Insect processing includes pre-processing, fractionation, grinding, and secondary processing for product development. The use phase should include distribution, retail, cooking and utilisation. Infrastructure consists of buildings, machinery and equipment relevant to capital investments. Such modular conceptualisation of LCA approaches to insect production chains allows to systematically consider the most important components and parameters relevant for a reliable analysis, determine the proper FU, scale of production and impact assessment methodology.

The second component of the framework should include the modularisation of insect production chain according to the modularisation scheme (Figure 1) and LCIA approaches (Table 1). Determination of modules should allow for the identification of important production chain elements and relevant data required. Moreover, setting up the analysis based on proposed modules should support the balance model thinking crucial for the correct results in LCA. Identification of relevant LCIA methodology should eliminate further hurdles of results interpretation and comparability with other studies.

The third component of modular framework includes the consideration of a FU and production scale (Table 4). Changes in both these parameters can affect the results and alter the final outcomes and conclusions. Such an approach provides a justified and solid basis for conducting state-of-the-art LCA and enables a reliable comparison of LCA studies of different insect production chains.

The proposed approach has certain limitations. First, it is based on the standardised approach to the LCA, which currently does not include the impact on biodiversity. There are a few methods being developed, which can find the application and can be also accounted in insect production LCA studies. Another indirect aspect which can be considered in the future is the direct potential impact of insect production especially dealing with waste treatment on the health of workers. Potential negative consequences might include allergies or intoxications. Currently there is not enough information on the potential effects, especially if the safety measures are considered. In future studies such information should be included. Animal welfare of insect production could also be a potential assessment category included in future LCA studies.

6. Conclusions

The study was oriented to review current scientific literature to establish a modular framework for the determination of environmental contribution of different parts of insect production chains.

Most LCA studies concentrated on attributional approach with results presented for several impact categories. Analysed studies relied on diverse impact assessment methods (LCIA) which can be grouped into ReCiPe, IMPACT 2002+, CML, ILCD and separate indicators. The goal of reviewed LCA articles deals with estimation of environmental impact of insect production for food and feed purposes to waste and manure treatment scenarios. Most studies rely on primary data from pilot insect production or on mix of primary data and information from

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the literature. There is a lack of studies, which would include the transportation and distribution of insect biomass/products, as most studies concentrate on cradle-to-gate approach.

The studies also reflected on environmental hot spots, which included production of feed (in case of commercial feed), insect cultivation and processing. Most impacts are associated with use of energy (electricity, fuel, natural gas). These factors are associated with high impacts in categories of global warming potential, non-renewable energy use, water and land use. Type of feed and modelling of its assessment was in many cases decisive for the determination of environmental impact of insects. Selection of by-product allocation rules, substitution criteria and waste scenarios determined the wide ranges of environmental impacts presented for food processing by-products, food waste and manure. Most LCA studies concentrated production of three insect species: *Hermetia illucens*, *Tenebrio molitor* and *Musca domestica*. Other five species are covered by single studies.

The analysis indicated that research literature is very diverse in the scope and boundaries of the LCA, selection of FU, LCIA methodologies, assessed insect species, scale of production and other aspects. For performing further LCA studies a systemised modular approach was suggested. It consists of three stages: (1) determination of system boundaries of insect production chains and relevant comparable studies via graphical mapping; (2) the modularisation of insect production chain according to the modularisation scheme and LCIA approaches; (3) the consideration of a FU and production scale which may affect the results and alter the final outcomes and conclusions.

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Conflict of interest

The authors declare no conflict of interest.

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