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SUSINCHAIN
SUSTAINABLE INSECT CHAIN

Modular environmental and economic assessment system

Deliverable 42

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CHAPTER 1

INTRODUCTION

Chapter 1 – Introduction

Insect industry is advancing in Europe, with the current state of achieving industrial scale of insect production with automated robotized insect rearing and first-stage processing. There are quite a few companies in Europe, reaching large scale production farms. Advances in the development of insect industry of Europe are often associated with more favourable sustainability potentials of insects comparing to traditional protein sources for feed or food. Despite multiple studies on economic feasibility, social acceptance and environmental impact, many open questions are left for the industry to deal with. Among the critical issues are the safety of insect biomass and its resource efficiency.

Insects are considered as less environmentally impacting sources of proteins than meat products. However, in certain cases, their environmental impact might be in the range of impacts similar to chicken and pork products for nitrous oxide emissions (Oonincx 2017) and land use (Smetana et al. 2016). However, the level of impact highly depends on the diet, production system (technology readiness level TRL and scale), and species, as some of them lead to the increased emissions compared to others (Oonincx 2017). Available literature indicates the promising potential of some insect species as a substitute for commercially available feed ingredients (Rumpold and Schlüter 2014; Magalhães et al. 2017; Nyakeri et al. 2017; Renna et al. 2017; Allegretti et al. 2018). Many studies highlight the possibility to replace increasingly expensive protein sources of feed (fish meal and soybean meal) (Liu et al. 2017; Loponte et al. 2017), specifically feasible due to the potential of agri-food waste, municipal waste (Diener et al. 2011) or manure use for insect feeding (ur Rehman et al. 2017). Salomone and co-authors also note the potential of technologies based on *Hermetia illucens* as a more environmentally preferable alternative for the treatment of biowastes (Salomone et al. 2017). While another group of authors, led by Allegretti (2018), highlights better exergy to energy transformation compared to soymeal when renewability and digestibility were taken into account (Allegretti et al. 2018). Most of the findings are hardly usable by the industry, as they often report environmental impact on legally or technologically inappropriate feeding substrates, growing and processing technologies with lower TRL than currently existing in industry.

Systematisation of potential feeds (non-utilised sources of biomass suitable as feed for insects) is currently the key challenge for the insect industry. It can assure the cost-efficiency of production from one side and environmental sustainability from the other side. The holistic approach calls to establish a database of all the potential agents of food and feed supply chains, which could have excessive biomass. The establishment of a database of available side-streams and wastes can help identify favourable mixtures applicable as feed for insect species and not utilisable for other purposes. The first prototypes of such databases are being created within the scope of EU-funded thematic network "AFORVALOR" (grant agreement No 696394), FoodDatabse of DIL, and Circado Prototype (Rethink

Resource GmbH, Zurich, Switzerland). However, a complete database, applicable to the insect industry and usable for LCA analysis, is currently unavailable.

Furthermore, considering the industrial scale is important for developing specific industrial guidelines, product innovations, and reliable comparison with traditional protein sources. Most of the analyses of economic feasibility and environmental impact are performed on the small pilot scale or small industrial scale of production with a rate of 0.02-1 ton of insect biomass processed (dry weight basis) per day (Salomone et al. 2017; Halloran et al. 2017; Thévenot et al. 2018). The wide variety in the industrial levels of insect production and processing for food and feed purposes, as well as in potential feed sources, is currently not considered. Studies concentrate on separate systems of production, separate insect species, and only a few products, which does not allow for direct industrial application and viable recommendations for the selection of more environmentally efficient options. Even though such assessments are valuable for determining environmental hotspots of insect production, they do not represent the scale of industrial potential and, therefore, cannot be referred for economic and environmental impact relevance. Moreover, most of the studies are based on partial and aggregated data, including potential errors due to the high uncertainty levels.

Currently, it is well acknowledged that the lack of appropriate data is the biggest challenge for the wide implementation of sustainability guidelines in the industry. Life Cycle Assessment (LCA) is a methodology, which can provide viable answers and recommendations on environmental sustainability performance, but its application is currently limited to a few cases, not transferrable to wider applications as general guidelines. There are a few approaches suggested to cope with the data limitation in LCA practices. One way to deal with a lack of data is to rely on the estimation of energy of physical processes or specific energy required to achieve a certain state of biomass. This approach might be useful, but does not provide realistic approximations as the energy of equipment used in industry is higher than simply the energy of physical processes. Another approach is applying a generalised approximation from known relations between the complete consumption of resources and specific parts of it (Olivetti et al. 2013). Modular modelling for LCA is a viable approach for the construction of analytical frameworks and holistic production-consumption systems (Haupt et al. 2018), scale-up of separate processes and their further reconnections (Caduff et al. 2014; Piccinno et al. 2016), and selection of optimal routes for the production and processing (Steubing et al. 2016).

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 in setting up sustainable production right away from the design phase. Data availability is lacking in comparison to well established feed and food industries (Salomone et al. 2017; Bosch et al. 2019; Ites et al. 2020), which poses a challenge to the industry’s efficient design of a sustainable production system (Ites et al. 2020). At the same time, the assurance of sustainability (lower environmental impact) of insect products in comparison to conventional benchmarks on the market is crucial for the survival of 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.

To cope with the limitations of data in LCA practices for insect industry, SUSINCHAINS uses the modular approach to cover the complete spectrum of insect production and processing parameters. It will reply to pre-established LCA analysis of separate modules, responsible for each part of insect biomass production and processing. The construction of a modular framework started with identification of relevant modules for the assessment and key assessment points, critical to answer in order to model and assess sustainability of insect production chains. Moreover, the modular LCSA system is designed for testing with insect production stakeholders.

Further, a combination of the defined modular sustainability assessment framework with the probability process matrix of production and processing has been created based on the data from the food and feed industry. It will eventually be updated with optimisation algorithms to cover the missing data points and uncertainty levels (Gregory et al. 2016), and to formulate a complete spectrum of existing and emerging technologies (second year of the project). The results will be a holistic database applicable for the insect, food, and feed industries to identify the optimised production-processing-consumption chains based on a few key data points. In this way, SUSINCHAIN will reach the industrialisation of LCA applications in food and feed industry and, specifically, in insect production.

CHAPTER 2

LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA) AND MODULARITY

Chapter 2 – Life Cycle Sustainability Assessment (LCSA) and modularity

Sustainability assessment nowadays broadened not merely considering environmental life cycle assessment but also life cycle costing (LCC) and social life cycle assessment (SLCA), thus forming comprehensive life cycle sustainability assessment (LCSA). Despite the fact that it is a tool to support policies and performance-based regulations, its contents and meaning often leave two questions to practitioners to answer: to which definition one needs to adopt, and then what challenges may occur. In this sense, Klöpffer and Renner (Klöpffer and Renner 2007) and Klöpffer (Kloepffer 2008) characterized LCSA. They underlined the acknowledgment of the triple bottom line (TBL) model which proposed a straightforward scheme for life cycle sustainability assessment (LCSA): LCA+LCC+SLCA where each pillar stands for as abovementioned. However, German Oeko-Institut introduced the TBL-based life cycle through a method 'Produktlinienanalyse' in 1987 (Projektgruppe Ökologische Wirtschaft (Hrsg.) 1987). Later, Guinée, with co-authors (Guinée et al. 2011), adopted the definition of LCA and called it a framework rather than a method. It was also proposed to broaden the scope of LCA at time to cover all three dimensions of sustainability (people, planet, and prosperity) to enhance the level of analysis from product level to the sector and even economy wide levels focusing on technological, economic and behavioural relations.

A bibliometric analysis by Guinée (Guinée 2016) through the ISI Web of Science (WoS) covering the time span of 2000-2014 has clearly shown that while the vast majority of publications focused on the broadening of impacts, only a few studies have been carried out on broadening the level of analysis. Such a conclusion, however, may be related to the limitation of chosen search terms since some publications do not necessarily use the same terms. The main challenge mainly includes the lack of practical examples of LCSA, of data and appropriate methodology specifically for LCSA indicators, of an efficient way to communicate results of LCSA, and comprehensive uncertainty assessment.

The life cycle thinking (LCT) approach is aimed at a holistic conceptualisation of environmental issues (or other pillars of sustainability) at system level (Mont and Bleischwitz 2007). 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 analyzing indirect and rebound effects, allowing to eliminate unintended negative consequences associated with higher rates of consumption of environmentally efficient and cheaper products (Mont and Bleischwitz 2007; Hertwich 2008). , The classical application of LCA relates to the comparison of alternative products and minimization of trade-offs between them to select less environmentally impacting options (Cucurachi et al. 2019). Moreover, LCT is an outlining the basis for the Environmental Product Declaration (Schau and Fet 2008; Del Borghi 2013) and Product Environmental Footprint (Bach et al. 2018), included in the guidelines of the 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).

Life Cycle Assessment (LCA) consists of a few main components, concepts, and guiding factors. ISO standards define four main stages of LCA: (1) Goal and scope definition (2) Life cycle inventory (LCI); (3) Life cycle impact assessment (LCIA); and (4) Interpretation (ISO 14040 2006; ISO 14044 2006). Any LCA should include information on functional unit (FU), system boundaries, impact assessment methods, and timeframe (Thabrew et al. 2009). 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). Such conceptualisation allows for certain consistency between different studies and standardisation of results. Further chapters include a few examples of the indicated components concerning insect production chains.

The 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 assessing multiple alternative value chains within a production system. In conventional LCA, a product's life cycle is modelled from the cradle to the grave, representing one distinct value chain. 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 that 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 life cycle inventories (LCI). Based on these modular LCIs, life cycle impact assessment (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 modularization, meaning the suitable definition of modules to represent key choices within the production system. Beyond streamlined scenario analysis, modular LCA also enables optimization of value chains by using the module data as inputs to optimization models (Steubing et al. 2016) and can be useful in dealing with data limitations in the assessment of emerging technologies (Thomas et al. 2020).

CHAPTER 3

ENVIRONMENTAL HOTSPOTS OF INSECT PRODUCTION

Chapter 3 – Environmental hotspots of insect production

Identifying major impacting points of insect production was based initially on the analysis of available data, and LCA approaches to crystalise potentially practical approaches and data to be transferred into modular LCSA. 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 (van Zanten et al. 2018; Smetana et al. 2019b). Most studies employ multiple impact categories and characterisation factors to analyse the environmental impact of insect production. A wide variety of impact assessment methods is used. Separate indicators are mostly calculated early studies (Oonincx and de Boer 2012; Komakech et al. 2015; van Zanten et al. 2015; Joensuu and Silvenius 2017), while other studies rely on more aggregated methodologies, allowing for the inclusion of multiple indicators and endpoint aggregation (Table 1).

Feed selection and properties to a great degree, define the performance and environmental impact of the insect production system (Oonincx and de Boer 2012; Smetana et al. 2016, 2019b; Bosch et al. 2019; Ites et al. 2020). Moreover, this relation is not straightforward, as higher 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 sizes of insects, longer growing cycles, and higher conversion ratio (Smetana et al. 2016; Bosch et al. 2019). 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 (Smetana et al. 2016; Salomone et al. 2017; Bosch et al. 2019; Ites et al. 2020). Environmental impact of animal manure treatment with insect technologies could also improve environmental impact or its worsening depending on the impact of avoided treatment processes (Smetana et al. 2016; Roffeis et al. 2017, 2020; Smetana 2020).

Study	**Impact categories (characterization factor)**	**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

Study	Impact categories (characterization factor)	Impact assessment method	Attributional/ Consequential
(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

Table 1 – Life cycle impact assessment approaches in LCA studies of insect production

LCA studies of insect mass rearing rarely pay attention to the production options of the feed or the side-streams (by-product) allocation of impacts. Separation of the harvesting stage from production is aimed to define the impact of conventional feed production for animals, which many insect producers rely on due to the legislative limitations (Bosch et al. 2019). In commercial feed production, the boundaries for insect feed harvesting are comparable to those outlined for animal feeds (Smetana et al. 2016; Halloran et al. 2017; Bava et al. 2019; Bosch et al. 2019). The boundaries should include the classical agricultural stages of sowing, growing, and harvesting with further processing into animal feed. High availability of data and previously performed analyses (Papatryphon et al. 2004; McAuliffe et al. 2016; Poore and Nemecek 2018) make the assessment of insects produced on conventional feeds 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 consistency and representability.

Additionally, the boundaries for insect feed production sometimes include side-streams and secondary products from food processing or agriculture (Smetana et al. 2016; Bava et al. 2019; Bosch et al. 2019; Ites et al. 2020; Maiolo et al. 2020). It is envisioned that insect production in the future will be even stronger, relying 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). Insect feed formulations 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 (Smetana et al. 2016; Salomone et al. 2017; Mondello et al. 2017).

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 (van Zanten et al. 2018; Smetana et al. 2019b). The importance of this stage is also connected with the 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 (van Zanten et al. 2018; Smetana et al. 2019b).

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 (Smetana et al. 2016, 2019b; Ites et al. 2020). Feed is mostly delivered to insects in dried or high-moisture forms. Dried feeds are supplied to mealworms, crickets, and grasshoppers, while moisturized feeds are prepared for larvae of flies. Dried feeds, sources from grains require minimal processing, consisting of mixing, cutting, and grinding. In some cases, additional sources of moisture like vegetables are supplied alongside the dried feeds (Oonincx and de Boer 2012; Halloran et al. 2017). Moisturized 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 (Ravindran and Jaiswal 2019; Isibika et al. 2019) are not included in the examined LCA studies.

Insect farming, together with insect fractionation is 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 (Smetana et al. 2016, 2019b; Halloran et al. 2017; Thévenot et al. 2018; Bava et al. 2019; Maiolo et al. 2020). Therefore, the detailed analysis of insect farming and identification of improvement potential could play an important role. Direct metabolic emissions are indicated as neglectable (Mertenat et al. 2019; Ermolaev et al. 2019; Parodi et al. 2020).

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 detail, define these characteristics. Feed type and composition play an important role due to the upstream environmental impact associated with production (Oonincx and de Boer 2012; van Zanten et al. 2015; Halloran et al. 2017; Thévenot et al. 2018) or due to the amount of avoided impacts in case of waste treatment substitution (Salomone et al. 2017; Mertenat et al. 2019; Bava et al. 2019; Smetana 2020). Furthermore, feed conversion defines the efficiency of insect feeding and growing, as the lower the feed conversion ratio (FCR), the higher the performance of the production system and lower the environmental impact (for the similar impacting feeds). FCR, however, is not always transparently reflected in the studies. Different approaches include “wet to wet” (Oonincx and de Boer 2012; van Zanten et al. 2015; Halloran et al. 2017; Maiolo et al. 2020), “wet to dry” (Salomone et al. 2017; Roffeis et al. 2017, 2020), “dry to dry” (Smetana et al. 2019b; Bava et al. 2019) basis. Moreover, in some cases, only “ingested” feed was considered in the analysis of FCR (Oonincx and de Boer 2012; Halloran et al. 2017; Thévenot et al. 2018; Bava et al. 2019), 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 (Smetana et al. 2016, 2019b, Roffeis et al. 2017, 2020) 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.

Study	Feed type and components	Feed conversion	Residual biomass amount	Residual biomass management modelling
(Oonincx 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 fertilizer in consequential assessment, economic allocation in attributional part
(Komakech et al. 2015)	Organic waste and animal manure (theoretical)	Not provided		Insect frass is a soil improver/fertilizer, all impacts allocated to use of compost output; system expansion for (a) avoided fertilizer production and (b) 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 Chicken manure Cattle manure Food processing by-product: beet pulp Food processing by-product: distiller's dried grains with solubles (DDGS) Municipal organic waste	22-109 kg / 1 kg of meal and 0.9 kg lipids	Not provided	Insect frass is a fertilizer or treated as waste, mass and economic allocation
(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 fertilizer, for FU1: system expansion - avoided compost production; for FU2, 3: impact of bioconversion fully allocated to insect output (economic allocation, lower compost price)

Study	Feed type and components	Feed conversion	Residual biomass amount	Residual biomass management modelling
(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 fertilizer, system expansion - avoided fertilizer 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 fertilizer, all impact allocated to insect outputs; impacts from fertilizer out of scope
(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 fertilizer, system expansion - avoided fertilizer 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		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 fertilizer, 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 fertilizer; economic allocation for outputs (3.08:1 fresh insect: fertilizer)

Study	Feed type and components	Feed conversion	Residual biomass amount	Residual biomass management modelling
(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 fertilizer (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	8017 kg residue substrate and dead adult flies per 1000 kg insect meal	Insect frass is a fertilizer, 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 fertilizer, mass allocation; avoided production of fertilizer

Table 2 – Insect feeding characteristics

Energy use, GWP, energy use, 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 the resources used for insect rearing (Thévenot et al. 2018), climate system (Smetana et al. 2019b; Bava et al. 2019), and insect feeding (Smetana et al. 2016). However, a complete detailed picture is not presented.

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; Salomone et al. 2017; Thévenot et al. 2018; Ites et al. 2020). 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 the main feeding and growing into a separate facility. Sometimes the reproducing population gets another type of treatment, which ensures better reproduction performance. Despite a special treatment, the reproduction module is responsible for a minor impact in the scope of 2-3% (van Zanten et al. 2015; Smetana et al. 2019b), which is often excluded from the boundaries of LCA studies (Smetana et al. 2016; Ites et al. 2020) or combined with main production (Salomone et al. 2017; Smetana et al. 2019b; Bava et al. 2019). 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, too limited data are available for a transparent analysis.

Study	Species	Family	Order	Life stage studied
(Komakech et al. 2015; Smetana et al. 2016, 2020a; Salomone et al. 2017; Roffeis et al. 2017, 2020; Bava et al. 2019; Bosch et al. 2019; Ites et al. 2020; Maiolo et al. 2020)	*Hermetia illucens*	*Stratiomyidae*	*Diptera*	Larval/pre-pupae
(Mertenat et al. 2019; Smetana et al. 2019b)	*Hermetia illucens*	*Stratiomyidae*	*Diptera*	Larval/adult
(Oonincx and de Boer 2012; Smetana et al. 2015, 2020a; Joensuu and Silvenius 2017; Ites et al. 2020)	*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

Table 3 – Insects investigated in LCA studies

Insect production can result in a few potential products ranging from fresh live insects to fractionated and incorporated intermediates. All these products need proper storage to ensure longer preservation and their safety till product development and distribution. These steps are rarely described in LCA studies, with a few exceptions (Smetana et al. 2015, 2020a).

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. Secondary processing targets getting improved insect-derived components through operations like milling, fractionation via centrifugation, drying, and fat separation. The differences in processing result in various end products sold to a business or final consumers: whole live insects, whole fresh/frozen insects, fresh insect puree, whole dried larvae, defatted meal, insect oil, intermediate products containing insect components. Variations in the extent of processing 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 live insects, suitable mostly for feed application (Oonincx and de Boer 2012; Komakech et al. 2015; Bosch et al. 2019; Suckling et al. 2020). Application of alive larvae for direct food consumption is doubtful as currently, no companies are 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 (Roffeis et al. 2015; Salomone et al. 2017; Halloran et al. 2017; Mertenat et al. 2019; Bava et al. 2019; Ites et al. 2020). Most studies, however, are concentrated on the assessment of fractionated or incorporated insect products in cradle-to-processing gate or plate boundaries (van Zanten et al. 2015; Smetana et al. 2015, 2016, 2019b, 2020a; Thévenot et al. 2018; Ulmer et al. 2020; Maiolo et al. 2020).

Secondary processing of insect biomass relates to the fractionation of insects into a few fractions: water, lipid, and protein. The purity of fractionation depends on the 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 (Salomone et al. 2017; Roffeis et al. 2017, 2020; Mertenat et al. 2019; Smetana et al. 2019b; Bava et al. 2019; Ites et al. 2020). It can have a relatively high energy demand and could result in high associated environmental impacts. In some cases, the heat used for insect production could be sourced as a by-product of other industries, thus having low environmental impacts (Joensuu and Silvenius 2017). In other cases, when high quality of insect biomass should be assured for food applications, e.g., drying is relying on lyophilisation technologies (freeze-drying of whole larvae) (Lenaerts et al. 2018; Bava et al. 2019), it is associated with high energy expenses and relatively high environmental impacts.

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

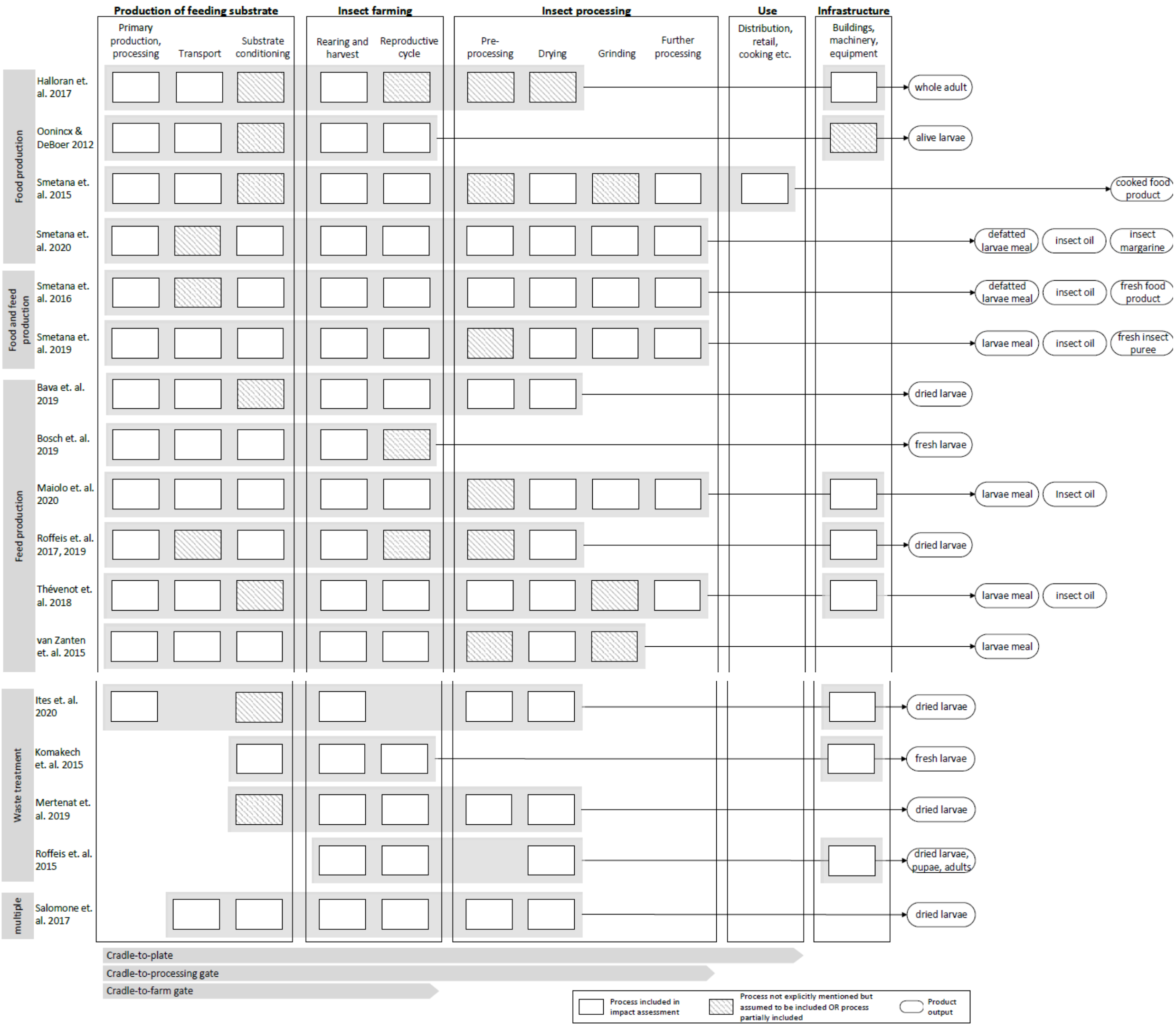

Figure 1 – Graphical mapping of insect production chains

Further product development is associated with the use of the concentrated protein fraction (insect flour, insect meal, or defatted protein concentrate) and of insect lipids (fats and 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 (Surendra et al. 2016; Zorrilla and Robin 2019; Gasco et al. 2020) 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 pelletizing 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. They are 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 (Tzompa-Sosa et al. 2019; Delicato et al. 2020), or as a part of complex fat products such as spreads and margarines (Smetana et al. 2020a). There are only a a couple of studies which performed LCA research in the scope of cradle-to-product application boundaries (Fig. 1), even though cooking of the product at the 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 (Oonincx and de Boer 2012; Smetana et al. 2016, 2020a; Salomone et al. 2017; Halloran et al. 2017; Bava et al. 2019).

CHAPTER 4

CONCEPTUALISATION OF A MODULAR ASSESSMENT FRAMEWORK FOR INSECT PRODUCTION

Chapter 4 – Conceptualisation of a modular assessment framework for insect production

Despite the few studies presenting LCA results, there is an evident lack of systemized information, inhibiting comparisons with other insect products and production chains or conventional products. Insect production LCA studies are often performed at the lab-scale level, which does not allow for a direct result transfer to pilot or industrial scales (Table 4). Upscaling of insect production will likely decrease the environmental impact of insect products (Smetana et al. 2018a, 2019b; Heckmann et al. 2019). 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, waste, or manure for insect feeding can reduce the environmental impact of insect products (Komakech et al. 2015; van Zanten et al. 2015; Smetana et al. 2016; Salomone et al. 2017; Roffeis et al. 2017, 2020; Bosch et al. 2019; Ites et al. 2020). Furthermore, the impact of insect production can be reduced through the application of alternative energy sources (Smetana et al. 2016, 2019b), use of insects for additional ecosystem services tasks (pollination, biotransformation) (Ulmer et al. 2020), application of more efficient processing chains and the use of passive heating and cooling methods or application of live insects with minimal processing.

Studies	Unit	Scale of production/ assessment	Control diet	Impacts 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 and de Boer 2012; Oonincx et al. 2015)	FU1: GWP2: 3.1 FU2: 23-27	FU1: GWP2: 3.1	n/a

Studies	Unit	Scale of production/ assessment	Impacts		
			Control diet	Food processing by-product/food waste	Manure diet
(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
(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: (Thévenot et al. 2018; Smetana et al. 2019b)	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; CC: 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	

Note: CC - climate change in kg CO_2eq. (ILCD 2011); LU1 – land use in kg C deficit (ILCD 2011), WRD – water resource depletion in m^3 water eq. (ILCD 2011); GWP – global warming potential in kg CO_2eq. (not specified method); EU – energy use in MJ (not specified method); LU – Land use m^2 (not specified method);

GWP1 - global warming potential in kg CO_2eq. (IMPACT2002+); NRE – non-renewable energy consumption in MJ primary (IMPACT2002+); LO – land occupation m^2 org arable (IMPACT2002+); EU1 – energy use in MJ (separate indicator); GWP2: global warming potential 100 years in kg CO_2eq. (separate indicator); LU2 – land use in m^2, separate indicator; FD – fossil depletion kg oil eq. (ReCiPe); WD – water depletion in m^3 (ReCiPe); ALO – agricultural land occupation in $m^2yr_{agricultural\ land}$ (ReCiPe); GWP3 – global warming potential in kg CO_2eq. (ReCiPe); GWP4 – global warming potential in kg CO_2eq. (IPCC 2007); EU2 – energy use in MJ (CML 2); LU3 – land use in m^2a (CML 2); CC – climate change in kg CO_2eq. (CML2); WU – water use in L deprived (IMPACT World+); * - recalculated for 1 kg DM of whole larvae.

Table 4 – Characterisation of insect LCA studies according to the production scale and environmental impacts

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, optimization of growing conditions, level of processing, type of distribution, etc. 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 modularization of insect production stages and their analysis on a standardised scale. 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 to 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. 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. The 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 reliable analysis, determine the proper functional unit, the scale of production, and impact assessment methodology. Moreover, further analysis of the environmental impact of insect production chains can relatively easily map the feasible comparative basis relying on modularisation scheme of insect production chains (Figure 1), LCIA approaches (Table 1), and functional unit/production scale consideration (Table 4). Such an approach provides a justified and factual basis for conducting state-of-the-art LCA and enables a reliable comparison of LCA studies of different insect production chains.

CHAPTER 5

MODULAR FRAMEWORK FOR ASSESSMENT OF INSECT ENVIRONMENTAL AND ECONOMIC IMPACTS

Chapter 5 – Modular framework for assessment of insect environmental and economic impacts

In the context of sustainability, decision-makers often need to consider economic, environmental, and social aspects simultaneously. Such objectives transform decision-making into Multi-Criteria Decision Making (MCDM). While some approaches in the literature often propose solving MCDM using minimisation of total supply chain cost and environmental impacts (Mele et al. 2009), on the other hand, (Karayalcin 1982) primarily proposed the Analytical Hierarchy Process (AHP) method based on pairwise comparison for determining the weight for each unique criterion. Authors were able to study limited criteria with few indicators, however, due to the complexity of modelling various criteria there are a few works in supply chain design of agri-food. Regarding sustainability assessment of the insect supply chain, many indicators can be included in a two-stage multi-objective decision-making model.

This two-stage hybrid methodology primarily applies the Analytical Hierarchy Process (AHP) method, followed by the Ordered Weighted Averaging (OWA). The method then has been optimized in multi-objective mathematical model in order to design supply chain. Efficiency score can be calculated by performing the combination of APH and OWA and can further be used as an objective when applying mathematical models with multiple objectives applied. Following application of AHP, weights are calculated for selected criteria, which indicate the importance level and are exploited by OWA to retrieve an overall aggregated efficiency score for each alternative (module). In this way, each module can be evaluated based on specified criteria, and decision-makers can decide whether or not a filter is needed before further stage. One can apply the AHP method by structuring the hierarchy in which primarily started with the most general objectives to the most specific ones. One example of structuring is demonstrated as below (Figure 2).

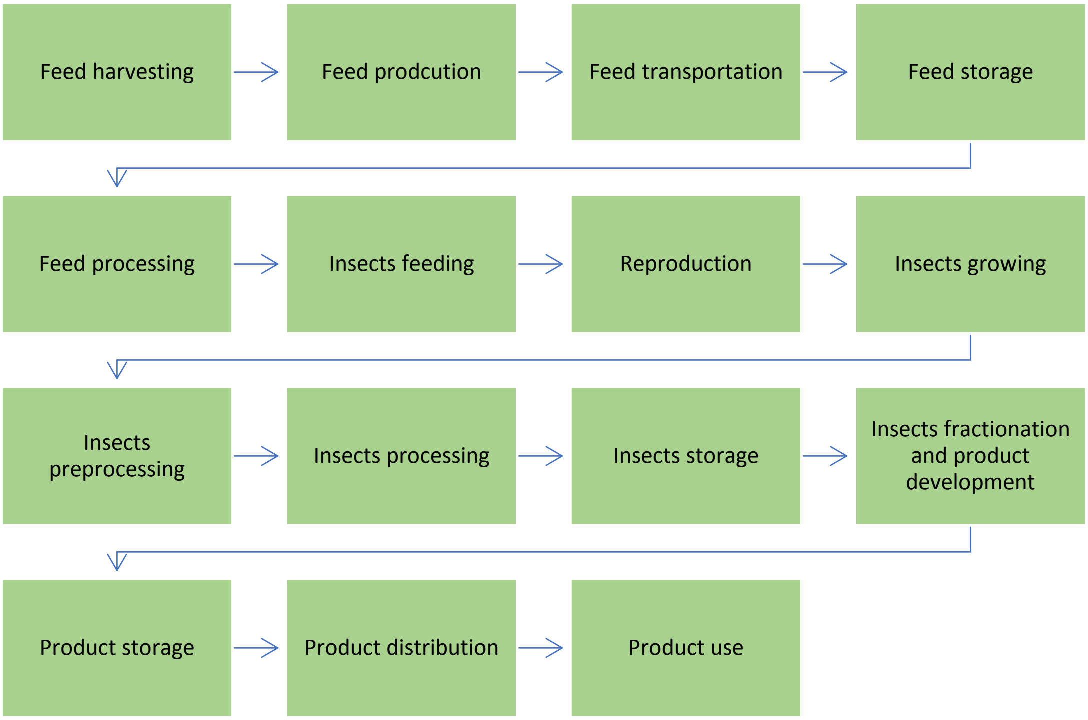

Figure 2 – Example of chain representation of insect production

Such a chain representation of insect production does not indicate which are the most impacting parts (economic and environmental). Both industrial companies and LCA practitioners are then inclined to analyse all the impacts step by step without tackling the most important parts. Such unstructured and unproductive approach should be tackled through a holistic approach.

One way to target impact assessment holistically is to perform a pairwise comparison of the AHP method is stored in matrix in which each eigenvector of the pairwise comparison matrix represents relative weight of indicators. In detail, a set of quantified judgments on a pair of indicators are demonstrated in a matrix as below with some requirements:

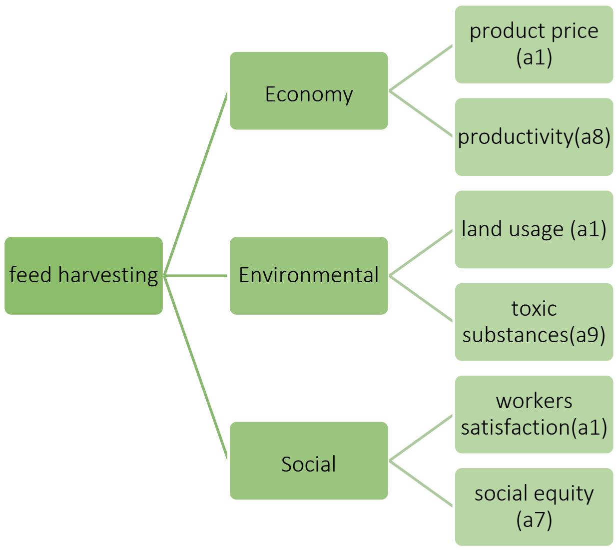

Figure 3 – An example of the hierarchical structure of decision making

Pairwise comparison of the AHP method is stored in matrices in which each eigenvector of pairwise comparison matrix represents relative weight of indicators. In detail, a set of quantified judgments on a pair of indicators are demonstrated in a matrix as below with some requirements:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1m} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

With the following rules:

- If $aij = x$, then $aji = 1/x$ $(x = 1,2,3 \ldots 9)$
- If $Ai = x$ is equal of relative intensity to Aj then $aij = ji = 1$
- $aii = 1$ for all i

Numbers are assigned according to relative intensity in the matrix. The weight vector is then the corresponding weight of indicators that represent their importance. OWA, hence, carried out to allow one to choose from "one criterion" to extreme "all the criteria." Application of OWA allows to specify numbers to linguistic measures, i.e., for the case of social dimensions, calculation of new weight, and generating overall efficiency score for each alternative. , The combination of AHP and OWA eventually resulted in the matrix of sustainability as below:

SUSINCHAIN modules (stages)	Sustainability aspects			Factor contribution
	Economic	Environmental	Social (input from other WPs needed)	
Feed Harvesting	Raw material cost (x1) Operational cost (x2) Production cost (x3) Transportation cost (x4) Transportation emission tax(x5) Opening/closing cost (x6) Capacity change cost (x7) Transport cost (x8) Energy tax (x9) Energy cost (x10) ...	Upstream impacts (y1) Production emissions (y2) Operational emissions (y3) Production water/energy/chemicals consumption (y4) Transportation emissions (y5) ...	Number of jobs created (z1) Workers satisfaction (z2) Social equality (z3) Direct health impact of product (z4) Direct health impact at production (z5) Market substitution effects (z6) ...	- Analytic hierarchy process (AHP) - Ordered weighted averaging (OWA) methods - Simultaneous consideration of three pillar of sustainability for sustainable streamlined assessment for supply chain design. - This requires to calculate weight for each sub criteria based on pairwise comparison.
Feed Production				
Feed Transportation				
Feed Storage				
...				
Overall score				

Table 5 – Sustainability matrix

Even though such an approach is feasible and holistic, its application by practitioners from industry is doubtful since it requires many inputs for understanding and considerable computing power. These aspects will be further explored in the SUSINCHAIN project via multi-objective optimization.

An industry relevant framework should consist of a limited number of key points (Figure 4), which would define the complete chain of insect production and predict (with 80% accuracy) the applied processes for insect production, processing, and distribution. The analysis of environmental and economic impacts of insect production (Chapters 1-4) allowed to define which type of insect (insect species) and their biological (ecological) needs would, to a great degree, define the production and processing chain.

Further key-point questions should include the type of feed and its amount supplied to the production concerning the insect produced. This point is the most important as it, to a great degree, defines the economic profitability and environmental impact of insect chains. Identifying the feed type would define the reliance of insect production on commercially available feeds or application of industrial side-streams or wastes for the cultivation. The total amount of feed used (not ingested) concerning amount of insect biomass and waste generated would indicate the efficiency of established insect production systems similarly as defined in animal production systems.

The most important part is the estimation of resources used in production and processing of insect production. The most viable approach is identifying gross energy (electricity, heating, fuel) and water resources used in company annually. Further relation of the number to annual production of insects would define quite precise number of such resources used.

The next question will refer to the definition of the final product. Type of product (fresh insects, dry insects, fractions of insect biomass, more complex formulations) will define the length of processing chain, and processing procedure applied. The processing methods themselves can be specified with two or three questions. The final part will include the specifications on packaging and distribution beyond the gate.

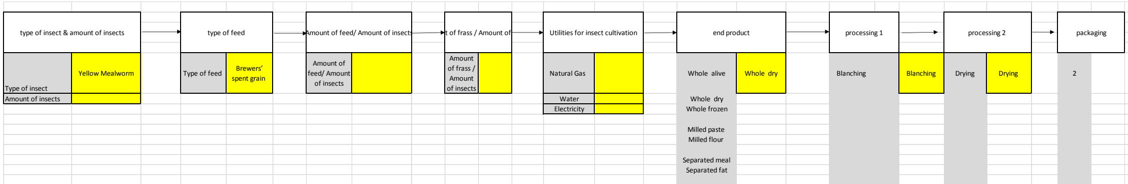

Figure 4 – Algorithm of identification of key point for the sustainability assessment using modular LCSA approach

Economic assessment of insect production is important, first of all, for the realistic identification of costs. When the costs are known, the price for the final product can be estimated to assure the desired return on investment and payback periods, etc. Economic cost assessment is quite similar to the environmental and would rely on the similar data collected. For the economic assessment, however, labour and/or automation costs would play the outmost importance as labour costs are quite high in Europe (labour costs are usually not considered in environmental impact).

The designed framework will be based on primary production and processing data, as well as data sourced from literature. The simplified model will generate outcomes indicating to what extent these data affect environmental, economic and social dimensions. This model will help insect producers and stakeholders identify hotspots along the insect supply chain against changes of LCSA dimensions. Following recognition of such hotspots, one could conclude optimal primary values to achieve the best case scenario of LCSA in insect production. The model will provide further recommendations to achieve sustainable insect production goals throughout the supply chain. This can mainly be achieved by diagrams when results are clarified. Such diagrams will demonstrate some recommendations to better consider three pillars of the sustainability.

Users need to insert the primary data in the excel file as below:

- Type of insect (among the type of insects such as House cricket, Black soldier fly larvae, House fly, Yellow mealworm)

- Type of feed (among the options already provided such as mill by-products, fruit, and vegetables, poultry feed (benchmark), brewers' spent grains)

- Amount of insects (unit is primarily set to 1 tonne)

- Amount of feed per selected amount of insects (this fraction need to be calculated by the user, and it defines the amount of initial feed per amount of initial insects in insect supply chains)

- Amount of frass per selected amount of insects (this fraction need to be calculated by the user stating quantities of frass (debris) per amount of initial insects)

- Natural Gas (the amount of gas used at the production in total inserted in kWh that helps to quantify environmental impacts as well as economic parameters)

- Water (water consumption in total per facility can be entered in $m^{3,}$ which can later be used to evaluate water footprint throughout the supply chain)

- Electricity (electricity used through insect production in total per the whole facility need to be entered in kWh, which can help evaluate the effects of electricity consumption on sustainability assessment indicators)

- End product (user can choose among available end products such as whole alive, whole dry, whole frozen, milled paste, milled flour, separated mill, and separated fat)

- Processing 1 (the technologies for first processing can be chosen from the list consists of blanching, decontamination, etc.)

- processing 2 (the second processing technologies need to be selected from a list encompasses drying, freezing, milling cooling, drying milling, etc.)

- Packaging (a list of packaging in the market can be assigned to each end product that its effects will also be evaluated on sustainability parameters)

Following completion of this stage, environmental impacts will be calculated. For economic part, some indicators like NPV (Net Positive value), payback will be calculated. These two sustainability dimensions will be aggregated into one part and translated into meaningful charts to help users gain a holistic view of the insect production chain.

CHAPTER 6

SUMMARY

Chapter 6 – Summary

The sustainability of insect production is typically cited as one of their advantageous properties. Insect production is booming in Europe, mostly due to the claimed efficiency compared to traditional protein sources. The increasing amount of literature on the efficiency of insect production and their applications, however, does not reflect on the potential impact of industrial upscaling. Most of the studies on insect production are focused on a small or pilot industrial scale and thus do not reflect the reality of the fast-evolving industry. The current analysis indicated that research literature is very diverse in the scope and boundaries of the LCA, selection of functional unit, LCA methodologies, assessed insect species, the scale of production, and other aspects.

The current study aimed to systemize previous studies to establish a modular framework for the determination of weights of sustainability assessment factors important for insect production chains. Reviewing published studies according to the elements of LCA, a feasible approach for the modelling of insect production chains was identified. It is based on a modular analysis of insect production through a graphical mapping of value chains (allowed identification of precise system boundaries) supplemented with probability analysis of processing and production technologies application. Such an approach allows for consistency in LCA setting and further comparability of results not only with insect production chain (studies) but also with benchmark systems. The most important factors necessary to model insect production chains were feed type and amount of produced insects and waste, amount of natural resources used at production (including processing), end product, and some determinants of processing and packaging. These factors are associated with high environmental and economic relevant impacts and responsible for the key criteria of sustainable insect production.

CHAPTER 7

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