Optimization models for sustainable insect production chains

N. Mouhrim[1, *], D. A. Peguero [2], A. Green[2], B. Silva[3], A. Bhatia[3], D. Ristic[3], A. Tonda[1], A. Mathys[2] and S. Smetana[3]

[1] UMR 518 MIA-PS, INRAE, Université Paris-Saclay, Palaiseau, France

[2] Sustainable Food Processing Laboratory, Institute of Food, Nutrition and Health, ETH Zurich, Zurich, Switzerland

[3] German Institute of Food Technologies (DIL e.V.), Quakenbrueck, Germany

[*] correspondance: nisrine.mouhrim@gmail.com

Abstract

Insect value chains are a complex system with non-linear links between many economic, environmental, and social variables. Multi-objective optimization (MOO) algorithms for finding optimal options for complex system functioning can provide a valuable insight in the development of sustainable insect chains. This review proposes a framework for MOO application that is based on gradual implementation, beginning with factors that have an immediate impact on insect production (feed qualities, resource utilization, yield), and progressing to integrated units (environmental, social, and economic impacts). The review introduces the key hotspots of insect production chains, which have been developed in suitable MOO objectives. They represent aspects of resource use, feed quality and its conversion by insects, labor safety and wage fairness, as well as environmental impacts. The capacity of the suggested MOO framework to describe all facets of sustainability may have certain limits. To determine the framework's applicability and the specific MOO algorithms that can perform the function, modeling and further testing on real insect production chains would be necessary for the intended objectives.

Keywords:

insect production sustainability, insect value chains, multi-objective optimisation of insect chains, insects for food and feed

1. Introduction

Assurance of a safe and environmentally sound protein supply is an urgent task in future food systems, as animal-sourced foods currently constitute the primary source of protein for most people and account for the largest share of environmental impacts in European diets (Sandström et al., 2018).. According to FAOSATAT, the world's average meats consumption in 2020 is 5,2 Mt (FAOSTAT Food and Agriculture Data). The amount of global consumption of animal protein could rise by 14% by 2030 compared to 2018-2020 (OECD-FAO), leading to extreme environmental consequences. There are a few promising alternative protein sources such as edible insects (Akhtar and Isman, 2018), single-cell proteins and tissue cultures, which can emerge in the food system and induce system changes when considering multiple sustainability dimensions (Green et al., 2022; Parodi et al., 2018a; Rubio et al., 2020; Smetana et al., 2017).

In Western countries, entomophagy, the human consumption of insects, is still met with some revulsion (Looy and Wood, 2015; Raheem et al., 2019; van Huis et al., 2013). Rather than a potentially nutritious food supply, insects are known as disease carriers (Butler et al., 2010) and often viewed as pests (Looy and Wood, 2015). Given the FAO recommendation for insects consumption as a possible solution to the world food supply's shortage, western consumer acceptance still continues to remain low (van Huis et al., 2013). For example, insect acceptance as a food product or ingredient in the European Union is the lowest at 9% compared to 84% for available alternative proteins (e.g., new plant, single-cell and in vitro proteins) (Grasso et al., 2019; Iannuzzi et al., 2019). Although studies show that consumers who have eaten insects before show a significantly more positive attitude towards repeating the experience (Lensvelt and Steenbekkers, 2014). In addition to being a potential food source for humans, insects are a valuable feed alternative for replacing other livestock feed such as fish and soy (Mat et al., 2022). Similar to the challenges facing insects as food, the acceptance of insects as feed remains a critical aspect of the insect rearing industry's development (Van Huis, 2013). However, the consumer receptivity to integrate insects in animal diets is related to various key factors, such as gender, food neophobia, and the impact of environmental messaging on consumers (Bazoche and Poret, 2020).

FAO defends that insect farming and/or gathering can increase employment in different regions, particularly for the lower classes of developing countries since insects can be used as food, feed, fiber collection, pest control and more (van Huis et al., 2013). The price of insects varies depending on the origin country and insect type sold. For instance, prices range from 10€/kg of termites in Kenya to 3.50 €/kg of canned fried crickets in Cambodia (Interreg NWE, 2020). Conversely, the cost can rise to around 107 €/kg of weaver ant pupae in the United Kingdom or almost 143 €/kg of migratory locusts in the Netherlands (Interreg NWE, 2020). This wide price range illustrates the diverse insect markets worldwide, and underscores the growing significance of the edible insect industry. With this, the edible insect market's worth is predicted to rise up to 1.96 billion by 2026, and 7.2 billion € by 2030 (Interreg NWE, 2020).

Alternative protein sources offer promising solutions to various pressing challenges, including addressing food security, improving human health, and mitigating environmental impacts (Sobczak

et al., 2023). In this context, insects emerge as a sustainable protein source for human consumption, as they efficiently convert feed into protein, requiring fewer resources (water, land, labor) and generating fewer emissions compared to traditional livestock (Skrivervik, 2020).
The justification on the sustainable benefits of alternative proteins is not straightforward and requires multi-perspective holistic assessment of complete value chains (Veldkamp et al., 2022), especially when the utilization of side-streams and wastes is involved in the production process (Smetana, 2020). Life Cycle Assessment (LCA) and other multicriteria studies dealing with production of insects, microalgae, fungi and mycoproteins, leaf proteins and underutilized plants for food and feed purposes identify wide ranges of results. Variations in approaches and methods, such as system boundaries and functional units create challenges for sustainability assessment comparisons between studies (Parodi et al., 2018b; Pleissner and Rumpold, 2018; Smetana et al., 2018). Furthermore, available sustainability studies are fragmented, not covering the whole spectrum of conditions (e.g., infrastructure, processing, product formulation), relying on various methodologies and different system boundaries for the assessment (Bosch et al., 2019; Smetana et al., 2021).

Insects as an alternative protein source have all the mentioned aspects of sustainability assessment challenges. There is a vast variety of insect species suitable for mass production for food and feed purposes (Ortiz et al., 2016), which can be produced on different feeding substrates affected by climate conditions of various locations (Oonincx et al., 2015; van Huis et al., 2021). Insects have different development cycles and can be utilized at various development stages (Halloran et al., 2016). They can serve as waste recirculation agents in food systems, returning nutrients to soils (Gold et al., 2018; Ojha et al., 2020; Poveda, 2021), feed (Ites et al., 2020) and even food (Smetana et al., 2020, 2019).

Such fragmentation and inconsistency in sustainability aspects (Macombe et al., 2019; Niyonsaba et al., 2021; Smetana et al., 2021; van Huis et al., 2021) indicate the need in the development of an integrated sustainability assessment framework, which would analyze different stages of insect production from multiple perspectives and define the optimal variants of production. A few insect producing companies and research teams involved in EU Horizon 2020 project SUSINCHAIN (SUStainable INsect CHAIN) highlight the demand for such a multi-objective optimization (MOO) tool in order "to contribute to novel protein provision for feed and food in Europe by overcoming the remaining barriers for increasing the economic viability of the insect value chain." (Veldkamp et al., 2022). To clarify, A MOO problem consists of simultaneously optimizing (i.e., looking for the minimum or the maximum) multiple conflicting objectives under several inequality and equality constraints and discrete or mixed variable types. MOO results in a set of trade-off solutions between the competing objectives known as Pareto optimal solutions instead of one single best solution.

The biggest advancements in evaluating multiple criteria (objectives) for the holistic sustainability assessment are connected to the need to integrate economic, social and environmental pillars (Azapagic et al., 2016; Florindo et al., 2020), combined with fuzzy logic algorithm and analytic hierarchy process methods (Florindo et al., 2020; Zheng et al., 2019), or using multidimensional Pareto optimization for economic and environmental aspects (Ostermeyer et al., 2013). While the application of multicriteria analysis in sustainability assessment studies is well described in literature, it is notably absent in studies dealing with insects.

Multi-objective optimization methods can be categorized into two groups: the Pareto and scalarization (Gunantara, 2018). Pareto methods are nature-inspired such as multi-objective metaheuristics, where a population represents a set of feasible solutions (Coello, 2009). The population is then developed iteratively throughout the mechanism of reproduction of selected individuals until a termination condition is met (Deb et al., 2016). The multi-objective methods can be based on various strategies, such as elitism, as illustrated by methods like Strength Pareto Evolutionary Algorithm 2 (SPEA2) and Non-dominated Sorting Genetic Algorithm II(NSGA-II) (Deb et al., 2000; Zitzler et al., 2001), decomposition, as exemplified by Multiobjective Evolutionary Algorithm Based on Decomposition (MOEA/D) (Qingfu Zhang and Hui Li, 2007), and dominance concepts, which include methods like dominance rank e. g., MultiObjective Genetic Algorithm (MOGA) (Fonseca and Fleming, 1993), dominance depth e.g., NSGA (Srinivas and Deb, 1994) and dominance count e.g., SPEA (Zitzler and Thiele, 1998). There are also multiple methods of scalarization that consists of converting a MOO problem into a simple objective problem. Among these methods we consider the well-known weighted sum method which consists of multiplying each objective by positive weights where each expresses the relative importance of the associated objective, the ε-constraint (Barichard, 2003) that consists of converting k-1 of the k objectives of the problem into constraints and separately optimize the remaining objective and the method goal programming (Zerdani 2013) that consists of minimizing the distance, according to a given metric, between the current solution and the aspirations of the decision-maker.

In the context of insect production, performance depends on the quality of feed used. However, there is a conflict between the environmental impact and economic value while choosing the feed (Smetana et al., 2021). Insects can be produced on waste, but then product safety, legal and social acceptance can become barriers (Chia et al., 2019; Van Huis, 2022). Given these various factors that affect insect value chains performance, it is necessary to develop a MOO framework for finding suitable compromises between the conflicting objectives of insect production. The objectives considered should account for the three aspects, namely environmental impact, societal concern and economic viability. The final goal of framework application and MOO modelling is to find a set of Pareto-optimal solutions, from which a human decision maker will eventually select one final compromise.

Considering the need in the development of an integrated framework for sustainability assessment of insect production chains (Veldkamp et al., 2022) and identification of Pareto optimal variants of chains (Smetana et al., 2021; Spykman et al., 2021), current conceptual review study is aimed to define the optimization models (objectives) for sustainable insect production chains. The review approach relied on the identification of environmental, social and economic hotspots described in literature dealing with insect production. It was followed by identification and development of mathematical models, describing different aspects of sustainability of insect production, which can be integrated in a multi-objective optimization framework.

2. Methodological approaches

Identification of sustainable hotspots

In Figure I, the process of growing insects (either for feed or food) is illustrated, though it can vary considerably, most of the time follows this general scheme. It typically begins with the production of feed ingredients, followed by the introduction of eggs or larvae (also known as seed larvae) in the rearing vessel together with the selected feeding substrate. The rearing units can be continuous or batch systems (Newton and Sheppard, 2012). The rearing process can take from a few days to several weeks, depending on the insect species and the stage of their life cycle they are harvested, as explained in (IPIFF, 2022; van Huis et al., 2013). Next follows harvesting of the insects, where the insects are separated from the frass. Frass consists of insect excrement, leftover feed together with dead insects or body parts such as shells, wings, legs and others (IPIFF, 2022). The last point of insect cultivation/production is insect processing. The processing route varies with the final product but mostly consists of steps like killing, washing, drying and fractionation (IPIFF, 2022; van Huis et al., 2013).

Insect production is similar to cattle production in the sense that both deal with animals and need similar inputs to grow and reproduce (European Commission, 2019). Type of feeding substrate and feed production system becomes one of the critical points defining the sustainability of insect production (Bosch et al., 2019). Most farmed insect species are omnivores which shows that their diet is flexible, meaning they can grow for several generations fed on suboptimal or alternative substrates (Ortiz et al., 2016). But current European legislation prohibits feeding substrates that are not of vegetal origin or is considered post-human consumption waste (European Commission, 2019).

A growing product range from insect production requires the implementation of specific legislation, standards, labelling and other regulatory instruments to protect consumers from possible health risks associated with their consumption. These risks can be biological (bacterial, viruses, fungi, parasites), chemical (e.g., mycotoxins, pesticides, toxic metals) or of other origins (FAO, 2021). Presently, there are some regulations in place for that end such as (European Commission, 2015) – this is because in the EU all insect-based products (whole insects, their parts or extracts) meant for human consumption fall under the name of "novel food products". Within the insect production chain, various activities within each production phase can have varying impacts on each sustainability dimension. For example, the type of substrate used during the rearing phase can have significant environmental impacts (Smetana et al., 2019) and economic aspects because of the feeds' influence on insect development times (Spykman et al., 2021). To determine impact improvement opportunities to be tackled in the developing framework, sustainability hotspots were identified along the production chain, as described in Table 1.

Establishment of an integrated framework of optimization models

The sustainable efficiency of insect production and consumption is influenced by multiple aspects, which cannot be systematically measured and analyzed. To achieve multi-objective optimization (MOO) for insect production chains, a specific framework structure should be established, leading to the determination of key objectives (goals of optimization), variables, constraints, and sustainability trade-offs.

The framework follows three main phases: (1) identification of data and information categories relevant to the objectives of the methodological framework; (2) development of the methodological framework through combination of existing models and/or development of new approaches for different objectives; and (3) validation and refining of the methodological framework (McMeekin et al., 2020). The proposed stages and steps of the integrated framework of MOO are divided into three main stages and nine steps (Table 2, which will be used to define key objectives and constraints relevant to the sustainability of insect production chains.

Identification of sustainable hotspots in insect value chains and relevant objectives, emphasize the need for systematic multi-objective optimization approach. A stepwise procedure is proposed, which begins with modeling value chain establishment and collection of data related to direct impact (production and quality of feed, insect biomass yield, generated wastes, as well as directly consumed resources). Further framework levels include integrated assessments applicable to the complete value chains targeting environmental (LCA), social (social impacts, e.g., fair wage), and economic (cost analysis) aspects. The final optimization stage deals with data interconnection and interoperation for the implementation of MOO algorithms. Application of defined framework to the insect production chains, makes it possible to define few key objectives and constrains relevant to sustainability of insect production chains.

Table 2. Proposed steps and stages of integrated framework of optimization models

Framework stages:	Steps of optimization models application
1. Modeling, biomass handling and resource use	(1) Value chain model establishment (material flow model, modular input-output frameworks) (2) Feed production and properties estimation (resource use, nutritional properties) (3) Direct use/transformation of biomass (feed conversion efficiency, amount of insect biomass generated, amount of frass produced) (4) Direct use of resources by insect production (energy, water, renewable energy)
2. Assessment and Economic analysis	(5) Integrated environmental impact in cradle-to-gate (grave) approach (LCA) (6) Fair wage potential (or similar) identification

	(7) Total annual cost analysis (e.g., CAPEX and OPEX combined)
3. Optimization	(8) Data management and interconnections identification (9) MOO algorithms application

3. Defined Objectives in MOO sustainable framework for insect production

In this paper, we defined a set of objectives for the purpose of optimizing insect production from a multi-objective perspective. The formulation of each objective aims to address specific concerns related to insect production and its impact on environment, society, and economy. In this section, we will introduce each of these objectives, their significance and their role in the multi-objective optimization framework for insect production. The set of objectives presents the foundation for our methodological framework, and consequently clear assessment of the sustainability of the insect value chain. The objectives are as follows:

Analysis of environmental aspects and resource efficiency

- Integrated environmental impact (ENV):

Insects are perceived as one of the environmentally preferred alternatives to currently used ingredients of food, feed, fuel and other industries (Ites et al., 2020; Manzano-Agugliaro et al., 2012; Mlcek et al., 2014). Such perception is associated with their relatively high feed conversion rate (1.7-3.6%) and ability to feed on a variety of materials, including some side-streams and waste materials (Gligorescu et al., 2020; van Huis, 2013). Environmental impact of insect production depends on a variety of factors - insect species, feed, farming conditions such as reducing food waste, as they can be used as a feed source for insects (Smetana et al., 2021) to name a few. In some cases, though, insects can have a relatively high environmental impact in energy use and global warming potential (Smetana et al., 2021). Accounting for the various aspects of environmental impacts of insect production stages is not a viable strategy, when multiple social and economic aspects are considered. Moreover, for construction of such a comprehensive system, compatibility and comparability between different studies are needed. It is especially important as even within research of insect production impacts, different system boundaries, methodologies, production scales or impact categories are used. It makes it very difficult to compare or integrate results of different studies (Smetana et al., 2021). There are two potential ways out for this problem: (1) select a limited number of environmental factors playing the crucial role; or (2) integrate the environmental impacts from different approaches in a similar single score. First approach, while viable, is limited due to the potential elimination of important environmental factors. While the second way faces the challenges of method standardization and might require further development (Bosch et al., 2020). Work on MOO, where compatibility is crucial for appropriate optimization, affirms the need for integrated environmental impact, able to provide compatible, standardized information and thus clear overview of the insect-production-centered flow of materials, energy, impacts and value. In this case, multi-objective optimization should incorporate a unified environmental impact score, consistently calculated across different stages of insect production. This entails adopting a modular approach to assess insect value chains (Spykman et al., 2021) and applying established Life Cycle Impact Assessment methods to consolidate impacts to a single score.

- Direct energy use (DEU):

DEU refers to the amount of energy needed throughout the insect production; it also includes the energy needed to produce feed for the insect. As the production of insects at scale is still new, optimizing energy use is key, because insect production can have high energy use impacts when compared to their alternatives (e.g., fishmeal, chicken). For example, one study found that cricket production at industrial scale could result in energy use values similar to that of chicken (Lundy and Parrella, 2015). Energy demands are considerable due to the controlled climate, including heating, needed during the rearing phase (van Huis and Oonincx, 2017). The heating is necessary because ambient temperatures dictate insect body temperatures; however, this also means that feeds can be used more efficiently (van Huis and Oonincx, 2017). Depending on the chosen insect feed, high energy use can also be associated with the feed production phase. Energy use is not always directly reported in studies; some only report global warming potential (GWP) or GHG emissions as metrics related to climate change. While DEU is not directly correlated with climate change impacts, a high energy use can indicate high climatic impacts. As energy decoupling becomes more prevalent with the advancements in renewable energy, a high DEU will not be linked to as high of climate impacts. The potential for this is briefly discussed in the following section.

- Renewable energy use share (RES)

As seen above, RES is an important factor in insect production systems. RES refers to the percentage of electricity and heat that is sourced from renewable energy. It is not intrinsically related to the production of insects; it is an external factor. However, the management of insect production could efficiently alter this aspect and thus change the impact on the environment. In conventional systems, RES is dependent on the national energy mix for the energy supply. Alternative choices for more sustainable sources of electricity, generated by solar or wind generators, as well as geothermal sources, provided by the suppliers, can be a viable strategy for the improvement of resource efficiency and environmental impacts. Insect producing companies can specifically decide to purchase renewable energy for their operations. Options for this include buying certificates for renewable energy, using power purchase agreements to contract supply of renewable energy, purchasing renewable energy from utilities, or generating own renewable energy for consumption (IRENA, 2018). A higher renewable energy share is largely desirable because emissions, leading to global warming damages, are much higher in energy derived from fossil fuels (Sims et al., 2003). Currently, for the EU, RES is around 21% with a set target up to 40% in 2030 (European Commission, 2022). Such information indicates that increases in RES will make insects much more sustainable in terms of energy use.

- Direct water use (DWU)

Insect production chains require water for the multiple production phases (Rumpold & Schlüter, 2013), such as insect rearing phase and harvest phase (Table 1). Water footprint of insect production chains can have similar impact to other animal production systems. For example, one study found that crickets had a similar water use efficiency to chickens (Halloran et al., 2017). Furthermore, water use can vary substantially across insect species. Another study found that mealworms required almost ten times more water than cricket farming (Miglietta et al., 2015). As with energy use, high water use is also associated with the feed production phase and can vary considerably depending upon the substrate used (Ites et al., 2020; Roffeis et al., 2017). However, in most cases, water use for insect production that excludes the feed production phase is much lower than that of livestock systems (Halloran et al., 2017). While it is important to account for the water footprint (water use upstream, direct water use and water use downstream) for the insect production chains, in most cases it is not in the abilities of the insect production company to effectively change upstream and downstream processes. The reduction of the direct water consumption (use) on the other hand can be an efficient resource preservation strategy. DWU refers to the water supplied for the consumption (tap water) directly for the insect production stage. To date, DWU has only been quantified in a limited number of studies (Bava, et al. 2019, Ites, et al. 2020) but could serve as a viable and easy to account factor for the determination of water use efficiency.

- Feed conversion efficiency (FCE)

FCE refers to the ability of the insects to ingest and convert the amount of feed provided into insect biomass and is typically expressed in percentage dry mass (% DM). For insect production to successfully upscale and become a profitable business, insects' feeding conversion efficiencies on wastes and side streams need to increase and remain consistent. A major obstacle in upscaling is the inconsistency in insect performance when the nutritional composition of the feed slightly changes, leading to variability in produced insect biomass. Various factors can influence the feed conversion efficiency, such as, the insect species (Oonincx et al., 2015), type of feed and its nutritional composition (van Broekhoven et al., 2015), larval density (Deruytter and Coudron, 2022) and development times (Lalander et al., 2019). For example, Lalander et al. 2019, demonstrated the FCE (referred to as biomass conversion efficiency) for *Hermetia illucens* varied from 0.2 to 13.9% DM when reared on digested sludge and food waste, respectively, with development times ranging from 14 days to 42 days. To assist with increasing FCE on various types of feed and shortening development times, research has focused on formulating diets to increase performance and reduce the variability among the many types of feeds. For instance, Gold et al. 2020 formulated differing biowastes to have the same protein-to-non-fiber carbohydrates (NFC) ratios of 1:1 to increase and stabilize *H. illucens* performance among the wastes. Although the FCE (bioconversion rate) improved on the formulated feeds compared to the individual wastes, the FCE (described as bioconversion rate) still varied among the different formulated diets ranging from 15 to 32% DM (Gold et al., 2020). Further research is aiming to identify other nutritional factors that could reduce the variability in insect performance. However, the nutritional needs to improve feed efficiency may differ among different insect species: Oonincx (Oonincx et al., 2015) showed that four different insect species reared on the same feed (food waste and by-products) resulted in different FCEs. The two species more suitable for animal feed (e.g., Argentinean cockroaches and *H. illucens*) had higher conversion efficiencies compared to the edible insect species (e.g., *T. molitor* and house crickets). Therefore, identifying areas where to optimize FCE among various insect species would provide guidance to insect production facilities on how to create a more reliable and consistent production of insect biomass.

- Nutritional value of feed index (NVF)

The NVF measures the nutritional value of insect feeds and is derived based on the concept of nutrient profiling algorithms, which are extensively used to rank food items and diets based on nutrient density. Examples of such algorithms include the nutrient-rich food (NRF) index and Nutrient Density to Climate Impact (NDCI) (Drewnowski and Fulgoni, 2008; Fulgoni et al., 2009; Smedman et al., 2010). They measure nutrient intakes against daily recommended nutrient intake values. We follow a similar approach to rank different feeds based on their nutrient density. Insects do not have well established recommended intake values for specific nutrients or components. They do, however, have baseline diets that experts have deemed to be optimal for insect performance (Cammack and Tomberlin, 2017; Hogsette, 1992). Thus, we equate these baseline diets to the daily recommended intakes mentioned earlier. This assumes that these current baseline diets are the ’golden’ standard for insects (with assumption that they will be further confirmed, improved and standardized). However, in the absence of more specific data, this is the best available option. Insect diets generally report ash content, protein, fat, carbohydrates, and amino acids. Thus, we include these in the NVF index. The index has a range of 0 to 100, with 100 indicating a perfect match of the baseline diet. A higher nutritional value means that the conversion efficiency might be higher which would be beneficial in terms of optimal outcomes.

- Amount of insect biomass (AIB) produced

The ability of a production system to supply the needed amount of biomass with required properties would to a great degree define the business relevance of an insect farm. Pilot industrial scale production of insects required a minimum reach of one ton per day of fresh weight insects (van Huis et al., 2013), however modern insect production facilities can produce 100-1,000 times higher amounts of biomass. Such a rapid increase in scale in just under a decade, and foreseen future increases, call for the analysis of available resources needed to produce insects, especially feed. Species destined for mass production should have high potential of biomass transformation; high feed conversion rate (1.7 for fresh weight); short development cycle; high survival and high oviposition rate, as well as potential to be used for food and feed. Available literature indicates that *H. illucens* and species of mealworm have a potential to transform low value food waste into usable biomass (rich in fats and proteins). *H. illucens* fed on brewery grains or expired food is more environmentally and economically efficient than composting and biogas production (Ites et al., 2020). Insect species accumulate proteins very efficiently – *Tenebrio molitor* utilizes 22-45% of dietary proteins, *H. illucens* larvae about half (43-55%), whereas an optimized diet leads to more efficient use of feed often available from commercial combined feeds (Allegretti et al., 2018; Magalhães et al., 2017; Orkusz, 2021; Renna et al., 2017). When it comes to renewability and digestibility of insect biomass, *H. illucens* has a better energy to energy efficiency than soymeal (Allegretti et al., 2018). The conversion efficiency from 75% lignin rich olive pomace residue to insect biomass is high, with 33% for protein, 79.76% for lauric acid, and 65.05% for palmitoleic acid (omega 7) (Ramzy et al., 2021). Nutritional value of insects (see further) could vary in quite a range, depending on the feed composition and conditions of growth. However, it can be hypothesized that the amount of produced insects (biomass) can serve as an indirect indicator of the impact of company production on the feed or food market.

- Amount of insect frass (AIFr) generated

Frass is an essential by-product from insect biomass production that can help boost the commercial viability of insect farming systems by providing an extra revenue stream. Frass is a good soil amendment since it is high in carbon (C) and nitrogen (N) depending on the insect diet. *T. molitor* frass can be utilized to make high-quality bio adsorbents (van Huis et al., 2013; Yang et al., 2019), and *H.illucens* frass has the potential to be used as a biofertilizer (made from either poultry waste, brewery waste or green market waste) (Quilliam et al., 2020). One limiting factor for the frass application indicated in legal documents is the need for the frass hygienisation (treatment for 1 hour for 70 degrees Celsius) (Elissen et al., 2023). Such treatment may potentially affect the fertilizing properties of the frass. High nutrient availability after frass addition to soil might result in significant quick losses of C (as CO2, partly CH4) and N (specially N2O) gases and decreasing the ecological advantages associated with insect-based proteins (Halloran et al., 2017; Houben et al., 2021; Kagata and Ohgushi, 2012; Quilliam et al., 2020). Inclusion of insect frass into biogas production also shows promising outcomes, since it is a sustainable soil amendment and plant fertilizer. Gärttling et al. found that the frass produced by *H.illucens* had nutritional composition of 3.4% N, 2.9% P_2O_5 and 3.5% K_2O (Gärttling et al., 2020). The insect frass could be used to replace some artificial nitrogen fertilizers and offset their emissions (Poveda 2021). Thus, the amount of frass could serve as an indicator for the potential of insect production for the multifunctionality and thus for the more robust production system.

Analysis of social aspects

- Fair wage potential (FWP)

Social impacts of insect production chains are currently poorly investigated. The only study (Macombe et al., 2019), highlights possible positive social effects associated with job creation, while negative impacts might be associated with allergy risks for the workers and potential disturbances to the neighborhoods. The last issue is suggested to be solved by the careful selection of the locations for the insect production industry study (Macombe et al., 2019) and therefore can be eliminated from the important factors. Job creation, however, is a powerful aspect, which can determine the social success of the insect production chains. Therefore, it is necessary to define the weight of the factor in relation to variable conditions.

Income and wage are integrative and deterministic factors, reflecting the standard of life and well-being of workers. While it is not expected that wages in insect production are different than those of similar industries in the countries (Niyonsaba et al., 2021; Weinreis et al., 2023), they can serve as an integrated estimate for the overall position of insect production wages in a country. The characterization model of Fair Wage Potential (FWP) proposed by (Neugebauer et al., 2017) accounts for the actual wage paid at each step of production in comparison to a minimum living wage, relates to effective working time and includes an inequality factor to account for income inequalities. In this way, the weighting of FWP is related to the national conditions, while variations between different nations can be accounted for through additional relations. FWP proposed for the application in insect production chains is following the similar approach, but also includes the factor of income relations between different countries. It should be considered that this factor might not reflect high variations in the European Union but would reflect on any issues appearing in upstream and downstream processed and social impacts of insects produced in other countries.

- Labor safety (LS)

The level of worker safety (exposure to allergens, potential toxic substances, critical physical factors) is defined as an important factor reflecting potential negative social consequences of insect production (Macombe et al., 2019). Therefore, it is important to estimate the rate of exposure the workers can potentially get during insect production and/or the means to eliminate the potential impact. IPIFF Guide on Good Hygiene Practices for EU producers of insects as food and feed (IPIFF, 2022) equalizes the requirements regarding personal protective equipment (PPE) in the insect industry with those in food production facilities. PPE recommended for workers in insect production and processing facilities include ear plugs, helmets, glasses, gloves, masks and aprons. Therefore, one of the criteria defining the optimization models should be associated with the level of personnel protection with PPE. Such a criteria can be expressed through the cost of PPE supplied annually to the workers (Gurcanli et al., 2015) in relation to the scale of production (Table 3). Potentially, the relation of costs for PPE can be also expressed in relation to the different revenue streams or external investments, however, such relations require additional research.

Analysis of economic aspects

- Total Annual Cost (TAC)

Economic costs are a key driver of company performance and willingness to adopt new technologies. In a very general approach, it is usually divided into two main parts: cost and earnings, with the relation of those defining the profitability. It is quite hard to estimate the earnings of the insect producing companies, as there are a lot of potential selling channels with large price fluctuations on the market. Costs, on the other hand, should be always minimized and are usually well assessed by companies. Therefore, economic aspects of companies' performance were defined through costs calculation and indicating them as an objective to minimize.

4. Discussion

Integration of the proposed objectives in a framework

The proposed objectives, applicable for the MOO of insect production chains, can be computed and acquired using inputs from various public sources. It is recommended to follow the steps of the integrated framework for optimization models after exercising critical judgment since this paper proposes potential fragmentation of data (Table 2). The proposed steps are set according to the resources needed for a stakeholder to acquire the necessary data. Thus, the first stage of framework application indicates the set-up of the block-flow models with identification of feed amount and its properties, feed conversion efficiency, and amount of insect and frass generated. Together with the data on resources used (step 4) the framework sets the first level of the MOO application used for the core of the insect production chain (Figure II). These aspects are integrating a few key criteria and are directly related to the production of insects. Next step includes the calculation and integration of other external and separate aspects such as environmental impacts, social and economic factors. And the last, third step includes the MOO algorithms application.

Predicted functionality and application for multi-objective optimization

MOO can be applied to multiple objectives; however, it is currently efficient if applied for the optimization of two-six confronting aspects (Tanabe and Ishibuchi, 2020). The efficiency of MOO is limited due to the computing power but also with the ability to interpret the outcomes of the multi-objective analysis. Therefore, there is a potential to perform MOO with different triplets of objectives. It should be noted that the selection of three and more objectives could be performed in various combinations, but those combinations should not reflect the same characterization aspect. For example, combining direct energy use and water use, both aimed for minimization, would yield only scenarios with low resource use and would ignore the need for the high yield rates. Combining those objectives with feed conversion efficiency or amount of insect biomass produced would provide better MOO results. Therefore, the applicability of the proposed framework for the MOO of insect production relates to the selection of optimal solutions between the conflicting aspects, such as: nutritional quality of feed and feed conversion efficiency, renewable energy use and total cost, total annual cost, fair wage potential and environmental impact.

There are various approaches to combining objectives, and the choice depends on the specific problem addressed by the user of the framework, as well as their priorities and constraints.
Opting for a single objective and leaving out conflicting ones may not capture the full spectrum of trade-offs in the optimization problem. Conversely, considering the conflicting objectives allows users of the framework to gain insights into the trade-offs between different aspects of insect production.

The interpretation of the objective function depends on the chosen objectives. For example, if the user selects both economic and environmental objectives, the objective function becomes a weighted combination of economic and environmental performance metrics. Instead of optimizing for a single metric, users must now consider the trade-offs between these objectives. The objective function represents a compromise or balance between these chosen objectives, and the resulting solutions are located on a Pareto front, representing the best achievable trade-offs. As an illustration, for the economic aspect, we can choose the following sub-objectives: minimizing Total Annual Cost (TAC) while maximizing Fair Wage Potential (FWP). For the environmental aspect, we can select sub-objectives such as minimizing Direct Energy Use (DEU), minimizing Direct Water Use (DWU), and minimizing Integrated Environmental Impact (ENV). Additionally, we can incorporate social aspects into the framework. The optimization process aims to maximize Economic Viability while minimizing environmental impact. To achieve this, we normalize each sub-objective to establish a common scale and then combine them through scalarization. Scalarization involves assigning weights to each sub-objective to reflect its relative importance in achieving the overall objectives. Subsequently, we apply one of the MOO optimization algorithms, such as NSGA-II. The final outcome consists of a set of solutions that represent trade-offs between the objectives, from which the decision-maker can select the most suitable one.

In summary, the choice of objectives and their integration method should align with the goals and constraints of the optimization problem that the framework user is addressing. The integration of objectives is flexible and it depends on the specific needs of the user.

Interrelation of the sustainability hotspots of insect production chains

As seen previously, the hotspots of insect production are the production of feed, biomass farming and energy consumption, which is also supported by other studies (e.g., Smetana et al., 2021). The conceptual scheme of proposed criteria applicable to the insect production chains (Figure II) provides an overview of the connections between the selected parameters. This way, changes in one objective could cause a cascade of positive or negative effects changing the whole system. These parameters are divided into four groups according to the effect on the different aspects of sustainability: economic, environmental, social, and parameters that can be applied to a few aspects.

Insect feed production has a high impact because, even though insects can grow on suboptimal or alternative substrates, the current legislation prohibits most feed materials of animal origin or post-consumer waste (European Commission, 2009). Some formed foodstuffs (e.g., dairy and eggs) are exceptions[1]. The nutritional value of the feed affects the produced insect biomass: the more nutritious it is, the less amount is necessary to grow the insects. This reduces the costs and improves the profit margin. Feed conversion efficiency helps predict the amount of insect biomass produced. Consequently, affecting the amount of insect frass produced. Studies show that the impact of farming together with insect biomass fractionation ranges between 15 to 70% (Bosch et al., 2019; Smetana et al., 2021, 2019). This way, it also becomes important to analyze and break down the impacts in this category and refine them.

Some parameters are transversal to the entire process, for example, energy or water consumption (known as direct energy use or direct water use) that accounts for the total energy and water consumed in the processes during the production of insects. In the case of energy, it's still possible to see the share of renewable energy that is used through a third parameter. And lastly, the total annual costing looks at the accumulated cost of the entire process. To evaluate the impact of insect production, multiple objectives can affect or be affected by each other since they are all related, as seen in Figure II.

Envisioned limitations

Due to the novelty of using multi-objective optimization modeling for insect production, there are some envisioned limitations, as wide data gaps within the literature remain. Data on certain factors that may be of importance when finding the best possible solution is still lacking. For example, as discussed previously, social impact assessments have not been widely conducted, therefore, it may be difficult to reflect realistic scenarios or account for all possible alternatives when considering the social dimension. Additionally, with the data currently represented in the literature; many inconsistencies remain which need to be accounted for. For example, even within studies conducted

[1] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32016R0429

on the same insect species, such as *H. illucens*, there has not been a standardized approach on feeding experiments. Experimental conditions differ across studies, with differences ranging from starting weight of seed larvae to the rearing time prior to harvesting and climate conditions used, creating difficulty when wanting to compare and find the best solution. These differences may provide some limitations because of the inability to determine the underlying influence on insect performance. Therefore, a reader should carefully consider the fragmented nature of some data used for the analysis and model construction and use the outcomes with a critical approach. Another factor that could create a potential limitation is that lab scale data does not always accurately represent or translate to industry scale. For example, larval densities typically used within literature for *H. illucens* can range from 0.6 larvae/cm^2 (Isibika et al., 2019) to two larvae/cm^2 (Gold et al., 2020). However, these larval densities do not necessarily represent industry protocols, as industry suggests using larval density of three-five larvae/cm^2 (Dortmans et al., 2021). Current data on standards applied in industry are still lacking, which could lead to inaccuracy when evaluating different scenarios and their social, environmental, and economic impacts. The use of a scaling factor to translate lab scale data to industrial will be essential. The insect production chain is inherently complex, so deciding alternatives for each main activity along the value chain will require different sustainability criteria to be set.

Further work

Creating a multi-objective criteria optimization model could provide a more holistic approach on decision-making for optimizing the insect production chain. To assist in reducing limitations for optimization modeling, further work should consist of conducting more studies and gathering more data, especially from insect production facilities. The proposed framework and MOO scenarios should be tested with the field data to define the applicable objectives, algorithms and approaches. Additionally, a standardized approach on rearing insects and life cycle assessments (possibly through the development of Product Environmental Footprint Category Rules for insect production chains or for alternative proteins) should be implemented, so that data can become more consistent and comparable to generate optimal solutions reliably.

5. Conclusions

Insect value chains represent a complex system with indirect connections between quality and availability of feed, environmental impacts of production, economic and social factors. Such conditions create a basis for multi-objective optimization (MOO), aimed at finding optimal production chains influenced by multiple aspects. In order to apply the MOO efficiently, the following components should be defined: (1) identified sustainability hotspots representing environmental impact, societal concern and economic viability, which can fulfill the objective requirements and expressed in quantitative manner; (2) multi-objective optimization framework for describing different aspects of sustainability of insect production; (3) algorithm of MOO framework application.

The main environmental impact hotspots of insect production are associated with resource consumption of feed production, and various insect production phases. Application of alternative energy sources may reduce the energy-related impacts. Direct social impacts are associated with jobs created and employees' safety. Economic hotspots include the costs of production. Such aspects are the primary candidates for the MOO framework, consisting of three stages and structured around nine consecutive steps starting from insect production chain modelling through characterization of sustainability hotspots to the application of MOO algorithms. Proposed MOO framework for insect chains is designed for the gradual application targeting first factors directly influencing the production of insects (feed properties, resources use, yield) and moving to more integrated factors affecting environment, social and economic feasibility.

Proposed MOO framework might have certain limitations in ability to characterize all the aspects of sustainability. It would also require modelling and testing on the available data for the proposed objectives to define the applicability of the framework and specific algorithms of MOO which can serve the function.

Acknowledgements

Research is financially supported by the European Union's Horizon 2020 research and innovation program under grant agreement no. 861976 project SUSINCHAIN.

The project is partially supported by funds of the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the Federal Program for Ecological Farming and Other Forms of Sustainable Agriculture in the cope of H2020 ERA-net SUSFOOD2 and CORE Organic Cofund project "Poultrynsect" grant agreement 2819OE152. Research is partially funded by the German Federal Ministry of Education and Research (BMBF), in the frame of FACCE-SURPLUS/FACCE-JPI project UpWaste, grant number 031B0934A and of PRIMA project ADVAGROMED grant number 02WPM1651.

References

Akhtar, Y., and Isman, M.B., 2018. Insects as an Alternative Protein Source. Proteins in Food Processing (Second Edition)

Alexandratos, N. and Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision (No. 12– 03). FAO, ESA.

Allegretti, G., Talamini, E., Schmidt, V., Bogorni, P.C. and Ortega, E., 2018. Insect as feed: an emergy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. Journal of cleaner production 171: 403–412. https://doi.org/10.1016/j.jclepro.2017.09.244

Azapagic, A., Stamford, L., Youds, L. and Barteczko-Hibbert, C., 2016. Towards sustainable production and consumption: a novel DEcision-support framework Integrating Economic, Environmental and Social Sustainability (DESIRES). Computer and chemical engineering 91: 93–103. https://doi.org/10.1016/j.compchemeng.2016.03.017

Barichard, V., 2003. Approches hybrides pour les problèmes multiobjectifs. Université d'Angers.

Bava, L., Jucker, C., Gislon, G., Lupi, D., Savoldelli, S., Zucali, M. and Colombini, S, 2019. Rearing of *hermetia illucens* on different organic By-Products : influence on growth, waste reduction, and environmental impact. Animals 9(6): 289. https://doi.org/10.3390/ani9060289

Bazoche, P., & Poret, S. (2020). Acceptability of insects in animal feed: A survey of French consumers. Journal of consumer behavior.

Bosch, G., Oonincx, D.G.A.B., Jordan, H.R., Zhang, J., van Loon, J.J.A., van Huis, A. and Tomberlin, J.K., 2020. Standardisation of quantitative resource conversion studies with black soldier fly larvae. Journal of Insects as Food and Feed 6: 95–109. https://doi.org/10.3920/JIFF2019.0004

Bosch, G., Van Zanten, H.H.E., Zamprogna, A., Veenenbos, M., Meijer, N.P., Van Der Fels-Klerx, H.J. and Van Loon, J.J.A., 2019. Conversion of organic resources by black soldier fly larvae: legislation, efficiency and environmental impact. Journal of Cleaner Production 222: 355–363. https://doi.org/10.1016/j.jclepro.2019.02.270

Butler, J.F., Garcia-Maruniak, A., Meek, F. and Maruniak, J.E., 2010. Wild Florida house flies (*Musca domestica*) as carriers of pathogenic bacteria. Florida Entomologist 93: 218–223. https://doi.org/10.1653/024.093.0211

Cammack, J.A. and Tomberlin, J.K., 2017. The impact of diet protein and carbohydrate on select life-history traits of the black soldier fly *Hermetia illucens* (L.) (Diptera: Stratiomyidae). Insects 8: 56.

Chia, S.Y., Tanga, C.M., van Loon, J.J., Dicke, M., 2019. Insects for sustainable animal feed: inclusive business models involving smallholder farmers. Current Opinion in Environmental Sustainability 41: 23-30. https://doi: 10.1016/j.cosust.2019.09.003

Coello, C. C., Dhaenens, C., Jourdan, L. (Eds.)., 2009. Advances in multi-objective nature inspired computing 272

Deb, K., Sindhya, K., & Hakanen, J., 2016. Multi-objective optimization. In Decision sciences 161-200.

Deb, K., Agrawal, S., Pratap, A. and Meyarivan, T., 2000. A fast elitist Non-dominated Sorting Genetic Algorithm for multi-objective optimization: NSGA-II. https://doi.org/10.1007/3-540-45356-3_83

Deruytter, D. and Coudron, C.L., 2022. The effects of density on the growth, survival and feed conversion of *Tenebrio molitor* larvae. Journal of Insects as Food and Feed 8: 141–146. https://doi.org/10.3920/JIFF2021.0057

Dincer, I., 1999. Environmental impacts of energy. Energy Policy 27: 845–854. https://doi.org/10.1016/S0301-4215(99)00068-3

Dortmans, B.M.A., Egger, J., Diener, S. and Zurbrügg C., 2021. Black soldier fly biowaste processing - A step-by-step guide. Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.

Drewnowski, A. and Fulgoni, V., 2008. Nutrient profiling of foods: creating a nutrient-rich food index. Nutrition Reviews 66: 23–39. https://doi.org/10.1111/j.1753-4887.2007.00003.x

Elissen, H., van der Weide, R., Gollenbeek, L., & Wevers, K., 2023. Legislative issues surrounding the application of insect larvae and compost worms for biobased valorization of manure, digestate and other organics (No. WPR-994). Stichting Wageningen Research, Wageningen Plant Research.

European Commission, 2022. REPowerEU: affordable secure and sustainable energy.

European Commission, 2019. REGULATION (EC) No 1069/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal [WWW Document]. URL https://eur-lex.europa.eu/eli/reg/2009/1069 (accessed 11.18.21).

European Commission, 2015. Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods, amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001 [WWW Document]. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:JOL_2015_327_R_0001 (accessed 12.6.21).

European Commission, 2009. REGULATION (EC) No 1069/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation). Official J Eur Union 300, 33.

Eurostat, 2021. SHARES (Renewables).

FAO, 2021. Looking at edible insects from a food safety perspective - challenges and opportunities for the sector. Rome. https://doi.org/10.4060/cb4094en

FAOSTAT Food and Agriculture Data. *FAOSTAT*, https://www.fao.org/faostat/en/#data/FBS Accessed 10 September 2023.

Florindo, T.J., Bom de Medeiros Florindo, G.I., Ruviaro, C.F. and Pinto, A.T., 2020. Multicriteria decision-making and probabilistic weighing applied to sustainable assessment of beef life cycle. Journal of Cleaner Production 242: 118362. https://doi.org/10.1016/j.jclepro.2019.118362

Fonseca, C.M. and Fleming, P.J., 1993. Multiobjective genetic algorithms, in: IEE Colloquium on Genetic Algorithms for Control Systems Engineering.

Fulgoni, V.L., Keast, D.R. and Drewnowski, A., 2009. Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods. Journal of Nutrition 139: 1549–1554. https://doi.org/10.3945/jn.108.101360

Gärttling, D., Kirchner, S.M. and Schulz, H., 2020. Assessment of the N- and P-Fertilization effect of black soldier fly (Diptera: Stratiomyidae) by-products on maize. Journal of Insect Science 20. https://doi.org/10.1093/jisesa/ieaa089

Gligorescu, A., Fischer, C.H., Larsen, P.F., Nørgaard, J.V. and Heckman, L.-H.L., 2020. Production and optimization of *hermetia illucens* (L.) larvae reared on food waste and utilized as feed ingredient. Sustainability 12: 9864. https://doi.org/10.3390/su12239864

Gold, M., Tomberlin, J.K., Diener, S., Zurbrügg, C., and Mathys, A., 2018. Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: a review. Waste Management 82: 302-318. https://doi.org/10.1016/j.wasman.2018.10.022

Gold, M., Cassar, C.M., Zurbrügg, C., Kreuzer, M., Boulos, S., Diener, S. and Mathys, A., 2020. Biowaste treatment with black soldier fly larvae: increasing performance through the formulation of biowastes based on protein and carbohydrates. Waste Management 102: 319-329. https://doi.org/10.1016/j.wasman.2019.10.036

Gouel, C. and Guimbard, H., 2019. Nutrition transition and the structure of global food demand. American Journal of Agricultural Economics 101: 383–403. https://doi.org/10.1093/ajae/aay030

Grasso, A.C., Hung, Y., Olthof, M.R., Verbeke, W. and Brouwer, I.A., 2019. Older consumers' readiness to accept alternative, more sustainable protein sources in the European Union. Nutrients 11: 1904. https://doi.org/10.3390/nu11081904

Green, A., Blatmann, C., Chen, C. and Mathys, A., 2022. The role of alternative proteins and future foods in sustainable and contextually-adapted flexitarian diets. Trends in Food Science and Technology 124: 250-258. https://doi.org/10.1016/j.tifs.2022.03.026

Gunantara, N., 2018. A review of multi-objective optimization: Methods and its applications. Cogent Engineering 5: 1502242. https://doi.org/10.1080/23311916.2018.1502242

Gurcanli, G.E., Bilir, S. and Sevim, M., 2015. Activity based risk assessment and safety cost estimation for residential building construction projects. Safety Science 80: 1–12. https://doi.org/10.1016/j.ssci.2015.07.002

Halloran, A., Hanboonsong, Y., Roos, N. and Kuyper, T.W., 2017. Life cycle assessment of cricket farming in north-eastern Thailand. Journal of Cleaner Production 156: 83–94. https://doi.org/10.1016/j.jclepro.2017.04.017

Halloran, A., Roos, N., Eilenberg, J., Cerutti, A. and Kuyper, T. W., 2016. Life cycle assessment of edible insects for food protein: a review. Agronomy for Sustainable Development 36: 57. https://doi.org/10.1007/s13593-016-0392-8

Hogsette, J.A., 1992. New diets for production of house flies and stable flies (Diptera: muscidae) in the laboratory. Journal of Economic Entomology 85: 2291–2294. https://doi.org/10.1093/jee/85.6.2291

Houben, D., Daoulas, G. and Dulaurent, A.-M., 2021. Assessment of the short-term fertilizer potential of mealworm frass using a pot experiment. Frontiers in Sustainable Food Systems 5. https://doi.org/10.3389/fsufs.2021.714596

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M. and van Zelm, R., 2016. ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. International Journal of Life Cycle Assessment 22: 138-147. https://doi.org/10.1007/s11367-016-1246-y

Van Huis, A., 2022. Edible insects: challenges and prospects. Entomological Research 52:161-177. https://onlinelibrary.wiley.com/doi/pdfdirect/10.1111/1748-5967.12582

Iannuzzi, E., Sisto, R. and Nigro, C., 2019. The willingness to consume insect-based food: empirical research on italian consumers. Agricultural Economics (Czech Republic) 65: 454–462. https://doi.org/10.17221/87/2019-AGRICECON

Interreg NWE, 2020. Edible insects: market prospects | Interreg NWE. URL https://www.nweurope.eu/projects/project-search/valusect/news/edible-insects-market-prospects/ (accessed 9.2.21)

Ites, S., Smetana, S., Toepfl, S. and Heinz, V., 2020b. Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. Journal of Cleaner Production 248: 119248. https://doi.org/10.1016/j.jclepro.2019.119248.

IPIFF, 2022. IPIFF guide on good hygiene practices for European Union (EU) producers of insects as food and feed.

IRENA, 2018. Corporate courcing of renewables: market and industry trends – REmade Index 2018. Abu Dhabi.

Isibika, A., Vinnerås, B., Kibazohi, O., Zurbrügg, C. and Lalander, C., 2019. Pre-treatment of banana peel to improve composting by black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae) larvae. Waste Management 100: 151–160. https://doi.org/10.1016/j.wasman.2019.09.017

Ites, S., Smetana, S., Toepfl, S. and Heinz, V., 2020. Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. Journal of Cleaner Production 248: 119248. https://doi.org/10.1016/j.jclepro.2019.119248

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G. and Rosenbaum, R., 2003. IMPACT 2002+: A new life cycle impact assessment methodology. International Journal of Life Cycle Assessment 8: 324–330. https://doi.org/10.1007/BF02978505

Kagata, H. and Ohgushi, T., 2012. Positive and negative impacts of insect frass quality on soil nitrogen availability and plant growth. Population Ecology 54: 75–82. https://doi.org/10.1007/s10144-011-0281-6

Lalander, C., Diener, S., Zurbrügg, C. and Vinnerås, B., 2019. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). Journal of Cleaner Production 208: 211–219. https://doi.org/10.1016/j.jclepro.2018.10.017

Lensvelt, E.J.S. and Steenbekkers, L.P.A., 2014. Exploring consumer acceptance of entomophagy: a survey and experiment in Australia and the Netherlands. Ecology of Food and Nutrition 53: 543-561. https://doi.org/10.1080/03670244.2013.879865

Looy, H. and Wood, J.R., 2015. Imagination, hospitality, and affection: the unique legacy of food insects? Animal Frontiers 5: 8–13. https://doi.org/10.2527/af.2015-0013

Lundy, M.E. and Parrella, M.P., 2015. Crickets are not a free lunch: protein capture from scalable organic side-streams via high-density populations of Acheta domesticus. PLos one 10, e0118785. https://doi.org/10.1371/journal.pone.0118785

Macombe, C., le Feon, S., Aubin, J. and Maillard, F., 2019. Marketing and social effects of industrial scale insect value chains in Europe: case of mealworm for feed in France. Journal of Insects as Food and Feed 5, 215–224. https://doi.org/10.3920/JIFF2018.0047

Magalhães, R., Sánchez-López, A., Leal, R.S., Martínez-Llorens, S., Oliva-Teles, A. and Peres, H., 2017. Black soldier fly (*Hermetia illucens*) pre-pupae meal as a fish meal replacement in diets for European seabass (Dicentrarchus labrax). Aquaculture 476: 79–85. https://doi.org/10.1016/j.aquaculture.2017.04.021

Manzano-Agugliaro, F., Sanchez-Muros, M.J., Barroso, F.G., Martínez-Sánchez, A., Rojo, S. and Pérez-Bañón, C., 2012. Insects for biodiesel production. Renewable and Sustainable Energy Reviews 16: 3744–3753. https://doi.org/10.1016/j.rser.2012.03.017

Mat, K., Abdul Kari, Z., Rusli, N. D., Rahman, M. M., Harun, H. C., Al-Amsyar, S. M., Mohd Nor, M. F., Dawood, M. A.O., & Hassan, A. M. (2022). Effects of the inclusion of black soldier fly larvae (Hermetia illucens) meal on growth performance and blood plasma constituents in broiler chicken (Gallus gallus domesticus) production. Saudi Journal of Biological Sciences 29: 809-815

McMeekin, N., Wu, O., Germeni, E. and Briggs, A., 2020. How methodological frameworks are being developed: evidence from a scoping review. BMC Medical Research Methodology 20: 173. https://doi.org/10.1186/s12874-020-01061-4

Miglietta, P., de Leo, F., Ruberti, M. and Massari, S., 2015. Mealworms for food: a water footprint perspective. Water 7: 6190–6203. https://doi.org/10.3390/w7116190

Mlcek, J., Rop, O., Borkovcova, M. and Bednarova, M., 2014. A comprehensive look at the possibilities of edible insects as food in Europe – a review. Polish Journal of Food and Nutrition Sciences 64: 147–157. https://doi.org/10.2478/v10222-012-0099-8

Neugebauer, S., Emara, Y., Hellerström, C. and Finkbeiner, M., 2017. Calculation of fair wage potentials along products' life cycle – Introduction of a new midpoint impact category for social life cycle assessment. Journal of Clean Production 143: 1221–1232. https://doi.org/10.1016/j.jclepro.2016.11.172

Newton, G.L. and Sheppard, D.C., 2012. Systems and methods for rearing insect larvae. WO 2012/115959 A2.

Niyonsaba, H.H., Höhler, J., Kooistra, J., van der Fels-Klerx, H.J. and Meuwissen, M.P.M., 2021. Profitability of insect farms. Journal of Insects as Food and Feed 7: 923–934. https://doi.org/10.3920/JIFF2020.0087

OECD-FAO, editor. AGRICULTURAL OUTLOOK 2021-2030. https://www.fao.org/3/cb5332en/Meat.pdf.

Ojha, S., Bußler, S. and Schlüter, O.K., 2020. Food waste valorisation and circular economy concepts in insect production and processing. Waste Management 118: 600–609. https://doi.org/10.1016/j.wasman.2020.09.010

Oonincx, D.G.A.B., Van Broekhoven, S., Van Huis, A. and Van Loon, J.J.A., 2015. Feed conversion, survival and development, and composition of four insect species on diets composed of food By-Products. PLoS One 10, e0144601. https://doi.org/10.1371/journal.pone.0144601

Orkusz, A., 2021. Edible insects versus Meat—Nutritional comparison: knowledge of their composition is the key to good health. Nutrients 13: 1207. https://doi.org/10.3390/nu13041207

Ortiz, J. M., Ruiz, A.T., Morales-Ramos, J.A., Thomas, M., Rojas, M.G., Tomberlin, J.K., Lv, Y., Han, R., Giroud, L. and Jullien, R.L., 2016. Insect mass production technologies, in: Insects as Sustainable Food Ingredients. Elsevier :153–201. https://doi.org/10.1016/B978-0-12-802856-8.00006-5

Ostermeyer, Y., Wallbaum, H. and Reuter, F., 2013. Multidimensional pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment. International Journal of Life Cycle Assessment 18: 1762–1779. https://doi.org/10.1007/s11367-013-0548-6

Parodi, A., Leip, A., de Boer, I.J.M., Slegers, P.M., Ziegler, F., Temme, E.H.M., Herrero, M., Tuomisto, H., Valin, H., van Middelaar, C.E., Van Loon, J.J.A. and Van Zanten, H.H.E., 2018b. The potential of future foods for sustainable and healthy diets. Nature Sustainability 1: 782–789. https://doi.org/10.1038/s41893-018-0189-7

Pleissner, D. and Rumpold, B.A., 2018. Utilization of organic residues using heterotrophic microalgae and insects. Waste Management 72: 227–239. https://doi.org/10.1016/j.wasman.2017.11.020

Poveda, J., 2021. Insect frass in the development of sustainable agriculture. A review. Agronomy Sustainable Development 41: 5. https://doi.org/10.1007/s13593-020-00656-x

Quilliam, R.S., Nuku-Adeku, C., Maquart, P., Little, D., Newton, R. and Murray, F., 2020. Integrating insect frass biofertilisers into sustainable peri-urban agro-food systems. Journal of Insects Food and Feed 6: 315–322. https://doi.org/10.3920/JIFF2019.0049

Raheem, D., Carrascosa, C., Oluwole, O.B., Nieuwland, M., Saraiva, A., Millán, R. and Raposo, A., 2019. Traditional consumption of and rearing edible insects in Africa, Asia and Europe. Critical Reviews in Food Science and Nutrition 59: 2169–2188. https://doi.org/10.1080/10408398.2018.1440191

Ramzy, R.R., El-Dakar, M.A., Wang, D. and Ji, H., 2021. Conversion efficiency of Lignin-Rich olive pomace to produce Nutrient-Rich insect biomass by black soldier fly larvae, *Hermetia illucens*. Waste and Biomass Valorization 13: 893-903. https://doi.org/10.1007/s12649-021-01546-3

Renna, M., Schiavone, A., Gai, F., Dabbou, S., Lussiana, C., Malfatto, V., Prearo, M., Capucchio, M.T., Biasato, I., Biasibetti, E., de Marco, M., Brugiapaglia, A., Zoccarato, I. and Gasco, L., 2017. Evaluation of the suitability of a partially defatted black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (Oncorhynchus mykiss

Walbaum) diets. Journal of Animal Science and Biotechnology 8: 57. https://doi.org/10.1186/s40104-017-0191-3

Roffeis, M., Almeida, J., Wakefield, M., Valada, T., Devic, E., Koné, N., Kenis, M., Nacambo, S., Fitches, E., Koko, G., Mathijs, E., Achten, W. and Muys, B., 2017. Life cycle inventory analysis of prospective insect based feed production in West Africa. Sustainability 9: 1697. https://doi.org/10.3390/su9101697

Rubio, N.R., Xiang, N. and Kaplan, D.L., 2020. Plant-based and cell-based approaches to meat production. Nature Communications 11: 6276. https://doi.org/10.1038/s41467-020-20061-y

Rumpold, B. A., & Schlüter, O. K., 2013. Potential and challenges of insects as an innovative source for food and feed production. Innovative Food Science and Emerging Technologies 17: 1–11. https://doi.org/10.1016/j.ifset.2012.11.005

Sandström, V., Valin, H., Krisztin, T., Havlík, P., Herrero, M. and Kastner, T., 2018. The role of trade in the greenhouse gas footprints of EU diets. Global Food Security 19: 48–55. https://doi.org/10.1016/j.gfs.2018.08.007

Sims, R. E., Rogner, H. H., & Gregory, K., 2003. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy policy 31: 1315-1326.

Skrivervik, E.,2020. Insects' contribution to the bioeconomy and the reduction of food waste. Heliyon 6: 2405-8440.

Smetana, S., 2020. Life Cycle Assessment of specific organic waste-based bioeconomy approaches. Current Opinion in Green and Sustainability Chemistry 23: 50-54. https://doi.org/10.1016/j.cogsc.2020.02.009

Smetana, S., Aganovic, K., Irmscher, S. and Heinz, V., 2018. Agri-Food waste streams utilization for development of more sustainable food substitutes. Designing Sustainable Technologies, Products and Policies 145–155.

Smetana, S., Leonhardt, L., Kauppi, S.-M., Pajic, A. and Heinz, V., 2020. Insect margarine: processing, sustainability and design. Journal of Cleaner Production 264: 121670. https://doi.org/10.1016/j.jclepro.2020.121670

Smetana, S., Sandmann, M., Rohn, S., Pleissner, D. and Heinz, V., 2017. Autotrophic and heterotrophic microalgae and cyanobacteria cultivation for food and feed: life cycle assessment. Bioresource Technology 245: 162–170. https://doi.org/10.1016/j.biortech.2017.08.113

Smetana, S., Schmitt, E. and Mathys, A., 2019. Sustainable use of *Hermetia illucens* insect biomass for feed and food: attributional and consequential life cycle assessment. Resources Conservation Recycling 144: 285-296. https://doi.org/10.1016/j.resconrec.2019.01.042

Smetana, S., Spykman, R. and Heinz, V., 2021. Environmental aspects of insect mass production. Journal of Insects as Food and Feed 7: 553–571. https://doi.org/10.3920/JIFF2020.0116

Sobczak, P., Grochowicz, J., Łusiak, P., and Zukiewicz-Sobczak, W., 2023. Development of Alternative Protein Sources in Terms of a Sustainable System. Sustainability 15: 12111.

Spykman, R., Hossaini, S.M., Peguero, D.A., Green, A., Heinz, V. and Smetana, S., 2021. A modular environmental and economic assessment applied to the production of *Hermetia illucens* larvae as a protein source for food and feed. International Journal of Life Cycle Assessment 26: 1959–1976. https://doi.org/10.1007/s11367-021-01986-y

Srinivas, N. and Deb, K., 1994. Multiobjective optimization using nondominated sorting in genetic algorithms. Evolutionary Computation 2: 221–248. https://doi.org/10.1162/evco.1994.2.3.221

Tanabe, R. and Ishibuchi, H., 2020. An easy-to-use real-world multi-objective optimization problem suite. Applied Soft Computing 89: 106078. https://doi.org/10.1016/j.asoc.2020.106078

Van Broekhoven, S., Oonincx, D.G.A.B., Van Huis, A. and Van Loon, J.J.A., 2015. Growth performance and feed conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets composed of organic by-products. Journal of Insect Physiology 73: 1–10. https://doi.org/10.1016/j.jinsphys.2014.12.005

Van Huis, A., 2013. Potential of insects as food and feed in assuring food security. Annual Review Entomology 58: 563–583. https://doi.org/10.1146/annurev-ento-120811-153704

Van Huis, A. and Oonincx, D.G.A.B., 2017. The environmental sustainability of insects as food and feed. A review. Agronomy Sustainable Development 37: 43.

Van Huis, A., Rumpold, B.A., Van der Fels-Klerx, H.J. and Tomberlin, J.K., 2021. Advancing edible insects as food and feed in a circular economy. Journal of Insects as Food and Feed 7: 935–948. https://doi.org/10.3920/JIFF2021.x005

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G. and Vantomme, P., 2013. Edible insects: Future prospects for food and feed security, FAO Forest. ed. FAO, United Nations, Rome.

Veldkamp, T., Meijer, N., Alleweldt, F., Deruytter, D., Van Campenhout, L., Gasco, L., Roos, N., Smetana, S., Fernandes, A. and Van der Fels-Klerx, H.J., 2022. Overcoming technical and market barriers to enable sustainable Large-Scale production and consumption of insect proteins in Europe: A SUSINCHAIN Perspective. Insects 13: 281. https://doi.org/10.3390/insects13030281

Weinreis, Y., Baum, C.M. and Smetana, S., 2023. Insect production as a novel alternative to livestock farming: exploring interest and willingness to adopt among German farmers.

Sustainable Production and Consumption 35: 28–39. https://doi.org/10.1016/j.spc.2022.10.004

Yang, S.-S., Chen, Y., Kang, J.-H., Xie, T.-R., He, L., Xing, D.-F., Ren, N.-Q., Ho, S.-H. and Wu, W., 2019. Generation of high-efficient biochar for dye adsorption using frass of yellow mealworms (larvae of Tenebrio molitor Linnaeus) fed with wheat straw for insect biomass production. Journal of Cleaner Production 227: 33–47. https://doi.org/10.1016/j.jclepro.2019.04.005

Zhang, Q. and Li, H., 2007. MOEA/D: A multiobjective evolutionary algorithm based on decomposition. IEEE Transactions on Evolutionary Computation 11: 712–731. https://doi.org/10.1109/TEVC.2007.892759

Zerdani, O. (2013). L'optimisation non linéaire multiobjectif (Doctoral dissertation, Tizi Ouzou-Mouloud Mammeri University)

Zheng, X., Easa, S.M., Yang, Z., Ji, T. and Jiang, Z., 2019. Life-cycle sustainability assessment of pavement maintenance alternatives: methodology and case study. Journal of Clean Production 213: 659–672. https://doi.org/10.1016/j.jclepro.2018.12.227

Zitzler, E., Laumanns, M. and Thiele, L., 2001. SPEA2: improving the strength Pareto evolutionary algorithm. TIK-report 103.

Zitzler, E. and Thiele, L., 1998. An evolutionary algorithm for multiobjective optimization: The strength pareto approach. TIK-report 43.

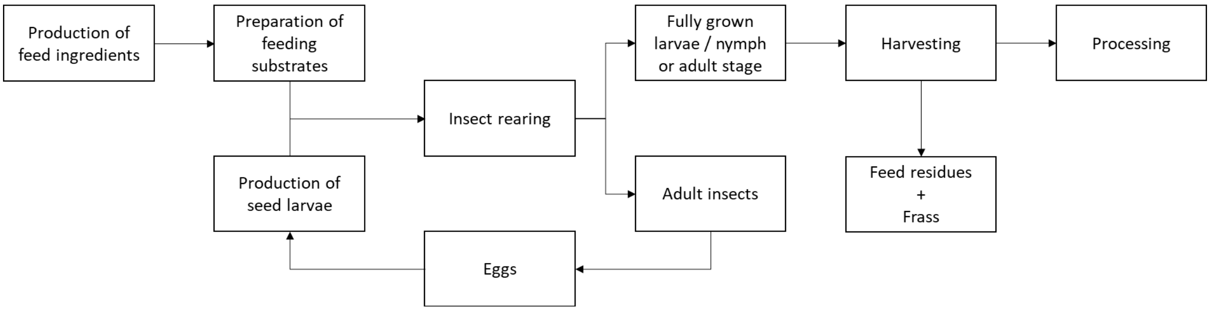

Figure I. Insect production system (Cortes Ortiz et al., 2016; IPIFF, 2022; Newton and Sheppard, 2012)

Table 1. Identified sustainability hotspots across the insect production chain. The production phases were adapted from (Spykman et al., 2021)

Insect production system		Environmental impacts			Social impacts	Economic impacts
Production phase	Activity	Resource use	Energy use	Emissions	Stakeholders	Costs/ Profitability
Feed preparation/ production	Production of feed ingredients/feed Transport of feed Preparation of feed for insect rearing	Water Land Feed ingredients	Diesel/fuel Electricity/ gas	GHG Wastewater and solid wastes	Creation of jobs	CAPEX /OPEX Transport cost
Breeding and nursery	Production of eggs Rearing of new hatchlings Maintenance of adults Maintenance of climate conditions	Water Land	Electricity/ gas Diesel/fuel	GHG Wastewater	Creation of jobs Allergy	CAPEX /OPEX Transport cost
Insect rearing	Distribution of feed to insects Maintenance of climate conditions	Water Land	Electricity/ gas	GHG Wastewater	Creation of jobs Allergy	CAPEX /OPEX Development time
Harvesting	Separation of insect from residue	Water	Electricity/ gas	GHG Wastewater	Creation of jobs Allergy	CAPEX /OPEX
Processing	Killing of insect Processing into desired product: Drying, fractionation, etc.	Water Land Detergents	Electricity/ gas	GHG Wastewater	Creation of jobs	CAPEX /OPEX
End-product handling	Human food Pet food Animal feed Frass	Packaging components	Fuel	GHG Packaging wastes	Creation of jobs Health risk	Retailer price Transport cost

Table 3. Main characteristics of defined objectives applied in MOO sustainable framework for insect production

Objective	Definition	Measurement unit (optimization aim)	Equation / Calculation methodology	Source
Amount of insect biomass (AIB) produced	Amount of insect biomass produced at the end of insect production chain as a main product (fresh or dried insects or fractions of biomass).	ton or kg (DM) (maximize)	$AIB = AIF * FCE$	Based on (Bosch et al., 2019)
Amount of insect frass (AIFr) generated	Amount of insect frass generated as a by-product of insect cultivation	ton or kg (DM) (minimize)	$AIFr = \left(\frac{AIF}{NVF}\right)(1 - FCE)\ FrSF$	Own equation
Direct energy use (DEU)	Direct resources used for insect production from feed preparation to climate system, inhouse transportation and processing (electricity, fuel and gas combined)	MJ or kWh (minimize)	$DEU = \left(E_e\left(\sum FP, CS, UTL, PRC\right) + E_h\left(\sum CS, UTL, PRC\right) + E_t\left(\sum TRW * L * H_e\right)\right) * EnergySF$	Own equation
Direct water use (DWU)	Direct water consumed (blue water) for insect production from feed preparation to climate system, inhouse transportation and processing	ton or m^3 (minimize)	$DWU = \left(\sum FP, CLS\right) * WaterSF$	Own equation

Integrated environmental impact (ENV)	Integrated environmental impact of insect production calculated by means of Life Cycle Assessment	Ecopoints (minimize)	IMPACT2002+; ReCiPe Endpoint or similar integrated methodology	(Huijbregts et al., 2016; Jolliet et al., 2003)
Feed conversion efficiency (FCE)	Efficiency of feed conversion of feed to insect biomass (classically defined as relation of amount of insect biomass to amount of insect feed)	% (maximize)	$FCE = FeedSF * NVF$	Own equation
Fair wage potential (FWP)	Fair wage potential representing the deviation from standardized salaries paid in the area and industry.	FWeq (maximize)	$FWP = \left(\frac{RW}{RWT}\right) CF_{FW}$	Neugebauer et al. 2017
Labor safety (LS)	Labor safety in a company measured as an annual supply (expenditure) of personal protective equipment for the workers	€ (maximize)	$LS = \left(\sum PPE_i * N_i\right) SF_{LS}$	Adapted from (Gurcanli et al., 2015)
Nutritional value of feed (NVF)	Measures the nutritional value of feed	Points (maximize)	$(NVF) = \sum \frac{1}{n} \times \left(\frac{Nutrients_f}{Nutrients_b} \times 100\right)$	Own equation
Renewable energy use share (RES)	Share of renewable energy used in insect production, based on statistical values from EUROSTAT, SHort Assessment of Renewable Energy Sources (SHARES), Suppliers of renewable energy sources and company data	% (maximize)	$RES = \%\,GridRenEn + \%CompRenEn + (\%SuplRenEn)$	Example: (Eurostat, 2021)
Total annual costing (TAC)	Total expenses of insect production calculated for annual values.	€ (minimize)	$TAC = Capex + Opex$	Corbetta et al. 2017

Note: DM – dry matter basis; AIF – amount of insect feed (dry matter basis); FrSF – frass scaling factor (depends on insect species, scale of production and growth conditions); E_e – electrical energy; FP – feed preparation (conditioning); CS – climate system; UTL – utilities; PRC – processing; E_h – heat energy; E_t – transportation energy (mostly fuels); TRW – transported weight; L – distance; H_e – heat energy of fuel; EnergySF – energy scaling factor (depends on insect species, scale of production); CLS – cleaning system; Water SF – water scaling factor (depends on insect species, scale of production); NVF – nutritional value of feed; FeedSF – feed scaling factor (depends on insect species, growth conditions); RW – real wages (€/month for annual period) paid to workers employed in process of insect production; RWT – real working time (hours/week) of workers involving in production process; CF_{FW} – fair wage related characterisation factor (month/€) for production process in relevant country, region and specific conditions; PPE – personal protective equipment cost, N – number of PPE units; SF_{LS} – scaling factor (depends on the scale of production and complexity of production chain); %GridRenEn – share of renewable energy in supply (country) mix (Eurostat, 2021); %CompRenEn – share of renewable energy supplied by the means installed in insect producing company; (%SuplRenEn) – optional measure (if data is available) of renewable energy share supplied by installed means in supplied companies. Capex - capital expenditure; Opex - operating expenditure; $Nutrients_f$ – nutrient amount in feed; $Nutrients_b$ – nutrient amount in baseline diet.