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1 Optimization models for sustainable insect production chains

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11

12 Abstract

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

26 Keywords:

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

1. Introduction

30 Assurance of a safe and environmentally sound protein supply is an urgent task in future food
31 systems, as animal-sourced foods currently constitute the primary source of protein for most people
32 and account for the largest share of environmental impacts in European diets (Sandström et al.,
33 2018).. According to FAOSATAT, the world's average meats consumption in 2020 is 5,2 Mt
34 (FAOSTAT Food and Agriculture Data). The amount of global consumption of animal protein
35 could rise by 14% by 2030 compared to 2018-2020 (OECD-FAO), leading to extreme
36 environmental consequences. There are a few promising alternative protein sources such as edible
37 insects (Akhtar and Isman, 2018), single-cell proteins and tissue cultures, which can emerge in the
38 food system and induce system changes when considering multiple sustainability dimensions
39 (Green et al., 2022; Parodi et al., 2018a; Rubio et al., 2020; Smetana et al., 2017).

40 In Western countries, entomophagy, the human consumption of insects, is still met with some
41 revulsion (Looy and Wood, 2015; Raheem et al., 2019; van Huis et al., 2013). Rather than a
42 potentially nutritious food supply, insects are known as disease carriers (Butler et al., 2010) and
43 often viewed as pests (Looy and Wood, 2015). Given the FAO recommendation for insects
44 consumption as a possible solution to the world food supply's shortage, western consumer
45 acceptance still continues to remain low (van Huis et al., 2013). For example, insect acceptance as
46 a food product or ingredient in the European Union is the lowest at 9% compared to 84% for
47 available alternative proteins (e.g., new plant, single-cell and in vitro proteins) (Grasso et al., 2019;
48 Iannuzzi et al., 2019). Although studies show that consumers who have eaten insects before show
49 a significantly more positive attitude towards repeating the experience (Lensvelt and Steenbekkers,
50 2014). In addition to being a potential food source for humans, insects are a valuable feed
51 alternative for replacing other livestock feed such as fish and soy (Mat et al., 2022). Similar to the
52 challenges facing insects as food, the acceptance of insects as feed remains a critical aspect of the
53 insect rearing industry's development (Van Huis, 2013). However, the consumer receptivity to
54 integrate insects in animal diets is related to various key factors, such as gender, food neophobia,
55 and the impact of environmental messaging on consumers (Bazoche and Poret, 2020).

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

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

68 et al., 2023). In this context, insects emerge as a sustainable protein source for human consumption,
69 as they efficiently convert feed into protein, requiring fewer resources (water, land, labor) and
70 generating fewer emissions compared to traditional livestock (Skrivervik, 2020).

71 The justification on the sustainable benefits of alternative proteins is not straightforward and
72 requires multi-perspective holistic assessment of complete value chains (Veldkamp et al., 2022),
73 especially when the utilization of side-streams and wastes is involved in the production process
74 (Smetana, 2020). Life Cycle Assessment (LCA) and other multicriteria studies dealing with
75 production of insects, microalgae, fungi and mycoproteins, leaf proteins and underutilized plants
76 for food and feed purposes identify wide ranges of results. Variations in approaches and methods,
77 such as system boundaries and functional units create challenges for sustainability assessment
78 comparisons between studies (Parodi et al., 2018b; Pleissner and Rumpold, 2018; Smetana et al.,
79 2018). Furthermore, available sustainability studies are fragmented, not covering the whole
80 spectrum of conditions (e.g., infrastructure, processing, product formulation), relying on various
81 methodologies and different system boundaries for the assessment (Bosch et al., 2019; Smetana et
82 al., 2021).

83 Insects as an alternative protein source have all the mentioned aspects of sustainability assessment
84 challenges. There is a vast variety of insect species suitable for mass production for food and feed
85 purposes (Ortiz et al., 2016), which can be produced on different feeding substrates affected by
86 climate conditions of various locations (Oonincx et al., 2015; van Huis et al., 2021). Insects have
87 different development cycles and can be utilized at various development stages (Halloran et al.,
88 2016). They can serve as waste recirculation agents in food systems, returning nutrients to soils
89 (Gold et al., 2018; Ojha et al., 2020; Poveda, 2021), feed (Ites et al., 2020) and even food (Smetana
90 et al., 2020, 2019).

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

104 The biggest advancements in evaluating multiple criteria (objectives) for the holistic sustainability
105 assessment are connected to the need to integrate economic, social and environmental pillars
106 (Azapagic et al., 2016; Florindo et al., 2020), combined with fuzzy logic algorithm and analytic

107 hierarchy process methods (Florindo et al., 2020; Zheng et al., 2019), or using multidimensional
108 Pareto optimization for economic and environmental aspects (Ostermeyer et al., 2013). While the
109 application of multicriteria analysis in sustainability assessment studies is well described in
110 literature, it is notably absent in studies dealing with insects.

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

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

140 Considering the need in the development of an integrated framework for sustainability assessment
141 of insect production chains (Veldkamp et al., 2022) and identification of Pareto optimal variants of
142 chains (Smetana et al., 2021; Spykman et al., 2021), current conceptual review study is aimed to
143 define the optimization models (objectives) for sustainable insect production chains. The review
144 approach relied on the identification of environmental, social and economic hotspots described in
145 literature dealing with insect production. It was followed by identification and development of

146 mathematical models, describing different aspects of sustainability of insect production, which can
147 be integrated in a multi-objective optimization framework.

148 **2. Methodological approaches**

149 *Identification of sustainable hotspots*

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

162 Insect production is similar to cattle production in the sense that both deal with animals and need
163 similar inputs to grow and reproduce (European Commission, 2019). Type of feeding substrate and
164 feed production system becomes one of the critical points defining the sustainability of insect
165 production (Bosch et al., 2019). Most farmed insect species are omnivores which shows that their
166 diet is flexible, meaning they can grow for several generations fed on suboptimal or alternative
167 substrates (Ortiz et al., 2016). But current European legislation prohibits feeding substrates that are
168 not of vegetal origin or is considered post-human consumption waste (European Commission,
169 2019).

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

183

184 *Establishment of an integrated framework of optimization models*

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

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

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

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

Framework stages:	Steps of optimization models application
<p>1. Modeling, biomass handling and resource use</p>	<p>(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)</p>
<p>2. Assessment and Economic analysis</p>	<p>(5) Integrated environmental impact in cradle-to-gate (grave) approach (LCA) (6) Fair wage potential (or similar) identification</p>

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

208

209

3. Defined Objectives in MOO sustainable framework for insect production

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

217

218 *Analysis of environmental aspects and resource efficiency*

219

- Integrated environmental impact (ENV):

220 Insects are perceived as one of the environmentally preferred alternatives to currently used
 221 ingredients of food, feed, fuel and other industries (Ites et al., 2020; Manzano-Agugliaro et al.,
 222 2012; Mlcek et al., 2014). Such perception is associated with their relatively high feed conversion
 223 rate (1.7-3.6%) and ability to feed on a variety of materials, including some side-streams and waste
 224 materials (Gligorescu et al., 2020; van Huis, 2013). Environmental impact of insect production
 225 depends on a variety of factors - insect species, feed, farming conditions such as reducing food
 226 waste, as they can be used as a feed source for insects (Smetana et al., 2021) to name a few. In
 227 some cases, though, insects can have a relatively high environmental impact in energy use and
 228 global warming potential (Smetana et al., 2021). Accounting for the various aspects of
 229 environmental impacts of insect production stages is not a viable strategy, when multiple social
 230 and economic aspects are considered. Moreover, for construction of such a comprehensive system,
 231 compatibility and comparability between different studies are needed. It is especially important as
 232 even within research of insect production impacts, different system boundaries, methodologies,
 233 production scales or impact categories are used. It makes it very difficult to compare or integrate
 234 results of different studies (Smetana et al., 2021). There are two potential ways out for this problem:
 235 (1) select a limited number of environmental factors playing the crucial role; or (2) integrate the
 236 environmental impacts from different approaches in a similar single score. First approach, while
 237 viable, is limited due to the potential elimination of important environmental factors. While the
 238 second way faces the challenges of method standardization and might require further development
 239 (Bosch et al., 2020). Work on MOO, where compatibility is crucial for appropriate optimization,
 240 affirms the need for integrated environmental impact, able to provide compatible, standardized
 241 information and thus clear overview of the insect-production-centered flow of materials, energy,
 242 impacts and value. In this case, multi-objective optimization should incorporate a unified

243 environmental impact score, consistently calculated across different stages of insect production.
244 This entails adopting a modular approach to assess insect value chains (Spykman et al., 2021) and
245 applying established Life Cycle Impact Assessment methods to consolidate impacts to a single
246 score.

247 • Direct energy use (DEU):

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

263 • Renewable energy use share (RES)

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

280 • Direct water use (DWU)

281 Insect production chains require water for the multiple production phases (Rumpold & Schlüter,
282 2013), such as insect rearing phase and harvest phase (Table 1). Water footprint of insect

283 production chains can have similar impact to other animal production systems. For example, one
284 study found that crickets had a similar water use efficiency to chickens (Halloran et al., 2017).
285 Furthermore, water use can vary substantially across insect species. Another study found that
286 mealworms required almost ten times more water than cricket farming (Miglietta et al., 2015). As
287 with energy use, high water use is also associated with the feed production phase and can vary
288 considerably depending upon the substrate used (Ites et al., 2020; Roffeis et al., 2017). However,
289 in most cases, water use for insect production that excludes the feed production phase is much
290 lower than that of livestock systems (Halloran et al., 2017). While it is important to account for the
291 water footprint (water use upstream, direct water use and water use downstream) for the insect
292 production chains, in most cases it is not in the abilities of the insect production company to
293 effectively change upstream and downstream processes. The reduction of the direct water
294 consumption (use) on the other hand can be an efficient resource preservation strategy. DWU refers
295 to the water supplied for the consumption (tap water) directly for the insect production stage. To
296 date, DWU has only been quantified in a limited number of studies (Bava, et al. 2019, Ites, et al.
297 2020) but could serve as a viable and easy to account factor for the determination of water use
298 efficiency.

299 • Feed conversion efficiency (FCE)

300 FCE refers to the ability of the insects to ingest and convert the amount of feed provided into insect
301 biomass and is typically expressed in percentage dry mass (% DM). For insect production to
302 successfully upscale and become a profitable business, insects' feeding conversion efficiencies on
303 wastes and side streams need to increase and remain consistent. A major obstacle in upscaling is
304 the inconsistency in insect performance when the nutritional composition of the feed slightly
305 changes, leading to variability in produced insect biomass. Various factors can influence the feed
306 conversion efficiency, such as, the insect species (Ooninx et al., 2015), type of feed and its
307 nutritional composition (van Broekhoven et al., 2015), larval density (Deruytter and Coudron,
308 2022) and development times (Lalander et al., 2019). For example, Lalander et al. 2019,
309 demonstrated the FCE (referred to as biomass conversion efficiency) for *Hermetia illucens* varied
310 from 0.2 to 13.9% DM when reared on digested sludge and food waste, respectively, with
311 development times ranging from 14 days to 42 days. To assist with increasing FCE on various
312 types of feed and shortening development times, research has focused on formulating diets to
313 increase performance and reduce the variability among the many types of feeds. For instance, Gold
314 et al. 2020 formulated differing biowastes to have the same protein-to-non-fiber carbohydrates
315 (NFC) ratios of 1:1 to increase and stabilize *H. illucens* performance among the wastes. Although
316 the FCE (bioconversion rate) improved on the formulated feeds compared to the individual wastes,
317 the FCE (described as bioconversion rate) still varied among the different formulated diets ranging
318 from 15 to 32% DM (Gold et al., 2020). Further research is aiming to identify other nutritional
319 factors that could reduce the variability in insect performance. However, the nutritional needs to
320 improve feed efficiency may differ among different insect species: Ooninx (Ooninx et al., 2015)
321 showed that four different insect species reared on the same feed (food waste and by-products)
322 resulted in different FCEs. The two species more suitable for animal feed (e.g., Argentinean
323 cockroaches and *H. illucens*) had higher conversion efficiencies compared to the edible insect
324 species (e.g., *T. molitor* and house crickets). Therefore, identifying areas where to optimize FCE

325 among various insect species would provide guidance to insect production facilities on how to
326 create a more reliable and consistent production of insect biomass.

327 • Nutritional value of feed index (NVF)

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

344 • Amount of insect biomass (AIB) produced

345 The ability of a production system to supply the needed amount of biomass with required properties
346 would to a great degree define the business relevance of an insect farm. Pilot industrial scale
347 production of insects required a minimum reach of one ton per day of fresh weight insects (van
348 Huis et al., 2013), however modern insect production facilities can produce 100-1,000 times higher
349 amounts of biomass. Such a rapid increase in scale in just under a decade, and foreseen future
350 increases, call for the analysis of available resources needed to produce insects, especially feed.
351 Species destined for mass production should have high potential of biomass transformation; high
352 feed conversion rate (1.7 for fresh weight); short development cycle; high survival and high
353 oviposition rate, as well as potential to be used for food and feed. Available literature indicates that
354 *H. illucens* and species of mealworm have a potential to transform low value food waste into usable
355 biomass (rich in fats and proteins). *H. illucens* fed on brewery grains or expired food is more
356 environmentally and economically efficient than composting and biogas production (Ites et al.,
357 2020). Insect species accumulate proteins very efficiently – *Tenebrio molitor* utilizes 22-45% of
358 dietary proteins, *H. illucens* larvae about half (43-55%), whereas an optimized diet leads to more
359 efficient use of feed often available from commercial combined feeds (Allegretti et al., 2018;
360 Magalhães et al., 2017; Orkusz, 2021; Renna et al., 2017). When it comes to renewability and
361 digestibility of insect biomass, *H. illucens* has a better energy to energy efficiency than soymeal
362 (Allegretti et al., 2018). The conversion efficiency from 75% lignin rich olive pomace residue to
363 insect biomass is high, with 33% for protein, 79.76% for lauric acid, and 65.05% for palmitoleic
364 acid (omega 7) (Ramzy et al., 2021). Nutritional value of insects (see further) could vary in quite
365 a range, depending on the feed composition and conditions of growth. However, it can be

366 hypothesized that the amount of produced insects (biomass) can serve as an indirect indicator of
367 the impact of company production on the feed or food market.

368 • Amount of insect frass (AIFr) generated

369 Frass is an essential by-product from insect biomass production that can help boost the commercial
370 viability of insect farming systems by providing an extra revenue stream. Frass is a good soil
371 amendment since it is high in carbon (C) and nitrogen (N) depending on the insect diet. *T. molitor*
372 frass can be utilized to make high-quality bio adsorbents (van Huis et al., 2013; Yang et al., 2019),
373 and *H. illucens* frass has the potential to be used as a biofertilizer (made from either poultry waste,
374 brewery waste or green market waste) (Quilliam et al., 2020). One limiting factor for the frass
375 application indicated in legal documents is the need for the frass hygienisation (treatment for 1
376 hour for 70 degrees Celsius) (Elissen et al., 2023). Such treatment may potentially affect the
377 fertilizing properties of the frass. High nutrient availability after frass addition to soil might result
378 in significant quick losses of C (as CO₂, partly CH₄) and N (specially N₂O) gases and decreasing
379 the ecological advantages associated with insect-based proteins (Halloran et al., 2017; Houben et
380 al., 2021; Kagata and Ohgushi, 2012; Quilliam et al., 2020). Inclusion of insect frass into biogas
381 production also shows promising outcomes, since it is a sustainable soil amendment and plant
382 fertilizer. Gärttling et al. found that the frass produced by *H. illucens* had nutritional composition
383 of 3.4% N, 2.9% P₂O₅ and 3.5% K₂O (Gärttling et al., 2020). The insect frass could be used to
384 replace some artificial nitrogen fertilizers and offset their emissions (Poveda 2021). Thus, the
385 amount of frass could serve as an indicator for the potential of insect production for the
386 multifunctionality and thus for the more robust production system.

387 *Analysis of social aspects*

388 • Fair wage potential (FWP)

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

397 Income and wage are integrative and deterministic factors, reflecting the standard of life and well-
398 being of workers. While it is not expected that wages in insect production are different than those
399 of similar industries in the countries (Niyonsaba et al., 2021; Weinreis et al., 2023), they can serve
400 as an integrated estimate for the overall position of insect production wages in a country. The
401 characterization model of Fair Wage Potential (FWP) proposed by (Neugebauer et al., 2017)
402 accounts for the actual wage paid at each step of production in comparison to a minimum living
403 wage, relates to effective working time and includes an inequality factor to account for income
404 inequalities. In this way, the weighting of FWP is related to the national conditions, while variations
405 between different nations can be accounted for through additional relations. FWP proposed for the

406 application in insect production chains is following the similar approach, but also includes the
407 factor of income relations between different countries. It should be considered that this factor might
408 not reflect high variations in the European Union but would reflect on any issues appearing in
409 upstream and downstream processed and social impacts of insects produced in other countries.

410 • Labor safety (LS)

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

424 *Analysis of economic aspects*

425 • Total Annual Cost (TAC)

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

433 **4. Discussion**

434 *Integration of the proposed objectives in a framework*

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

445 integration of other external and separate aspects such as environmental impacts, social and
446 economic factors. And the last, third step includes the MOO algorithms application.

447 *Predicted functionality and application for multi-objective optimization*

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

461 There are various approaches to combining objectives, and the choice depends on the specific
462 problem addressed by the user of the framework, as well as their priorities and constraints.

463 Opting for a single objective and leaving out conflicting ones may not capture the full spectrum of
464 trade-offs in the optimization problem. Conversely, considering the conflicting objectives allows
465 users of the framework to gain insights into the trade-offs between different aspects of insect
466 production.

467
468 The interpretation of the objective function depends on the chosen objectives. For example, if the
469 user selects both economic and environmental objectives, the objective function becomes a
470 weighted combination of economic and environmental performance metrics. Instead of optimizing
471 for a single metric, users must now consider the trade-offs between these objectives. The objective
472 function represents a compromise or balance between these chosen objectives, and the resulting
473 solutions are located on a Pareto front, representing the best achievable trade-offs. As an
474 illustration, for the economic aspect, we can choose the following sub-objectives: minimizing Total
475 Annual Cost (TAC) while maximizing Fair Wage Potential (FWP). For the environmental aspect,
476 we can select sub-objectives such as minimizing Direct Energy Use (DEU), minimizing Direct
477 Water Use (DWU), and minimizing Integrated Environmental Impact (ENV). Additionally, we can
478 incorporate social aspects into the framework. The optimization process aims to maximize
479 Economic Viability while minimizing environmental impact. To achieve this, we normalize each
480 sub-objective to establish a common scale and then combine them through scalarization.
481 Scalarization involves assigning weights to each sub-objective to reflect its relative importance in
482 achieving the overall objectives. Subsequently, we apply one of the MOO optimization algorithms,
483 such as NSGA-II. The final outcome consists of a set of solutions that represent trade-offs between
484 the objectives, from which the decision-maker can select the most suitable one.

485

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

489

490 *Interrelation of the sustainability hotspots of insect production chains*

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

499 Insect feed production has a high impact because, even though insects can grow on suboptimal or
500 alternative substrates, the current legislation prohibits most feed materials of animal origin or post-
501 consumer waste (European Commission, 2009). Some formed foodstuffs (e.g., dairy and eggs) are
502 exceptions¹. The nutritional value of the feed affects the produced insect biomass: the more
503 nutritious it is, the less amount is necessary to grow the insects. This reduces the costs and improves
504 the profit margin. Feed conversion efficiency helps predict the amount of insect biomass produced.
505 Consequently, affecting the amount of insect frass produced. Studies show that the impact of
506 farming together with insect biomass fractionation ranges between 15 to 70% (Bosch et al., 2019;
507 Smetana et al., 2021, 2019). This way, it also becomes important to analyze and break down the
508 impacts in this category and refine them.

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

516 *Envisioned limitations*

517 Due to the novelty of using multi-objective optimization modeling for insect production, there are
518 some envisioned limitations, as wide data gaps within the literature remain. Data on certain factors
519 that may be of importance when finding the best possible solution is still lacking. For example, as
520 discussed previously, social impact assessments have not been widely conducted, therefore, it may
521 be difficult to reflect realistic scenarios or account for all possible alternatives when considering
522 the social dimension. Additionally, with the data currently represented in the literature; many
523 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>

524 on the same insect species, such as *H. illucens*, there has not been a standardized approach on
525 feeding experiments. Experimental conditions differ across studies, with differences ranging from
526 starting weight of seed larvae to the rearing time prior to harvesting and climate conditions used,
527 creating difficulty when wanting to compare and find the best solution. These differences may
528 provide some limitations because of the inability to determine the underlying influence on insect
529 performance. Therefore, a reader should carefully consider the fragmented nature of some data
530 used for the analysis and model construction and use the outcomes with a critical approach. Another
531 factor that could create a potential limitation is that lab scale data does not always accurately
532 represent or translate to industry scale. For example, larval densities typically used within literature
533 for *H. illucens* can range from 0.6 larvae/cm² (Isibika et al., 2019) to two larvae/cm² (Gold et al.,
534 2020). However, these larval densities do not necessarily represent industry protocols, as industry
535 suggests using larval density of three-five larvae/cm² (Dortmans et al., 2021). Current data on
536 standards applied in industry are still lacking, which could lead to inaccuracy when evaluating
537 different scenarios and their social, environmental, and economic impacts. The use of a scaling
538 factor to translate lab scale data to industrial will be essential. The insect production chain is
539 inherently complex, so deciding alternatives for each main activity along the value chain will
540 require different sustainability criteria to be set.

541 *Further work*

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

551 **5. Conclusions**

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

561 The main environmental impact hotspots of insect production are associated with resource
562 consumption of feed production, and various insect production phases. Application of alternative
563 energy sources may reduce the energy-related impacts. Direct social impacts are associated with

564 jobs created and employees' safety. Economic hotspots include the costs of production. Such
565 aspects are the primary candidates for the MOO framework, consisting of three stages and
566 structured around nine consecutive steps starting from insect production chain modelling through
567 characterization of sustainability hotspots to the application of MOO algorithms. Proposed MOO
568 framework for insect chains is designed for the gradual application targeting first factors directly
569 influencing the production of insects (feed properties, resources use, yield) and moving to more
570 integrated factors affecting environment, social and economic feasibility.

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

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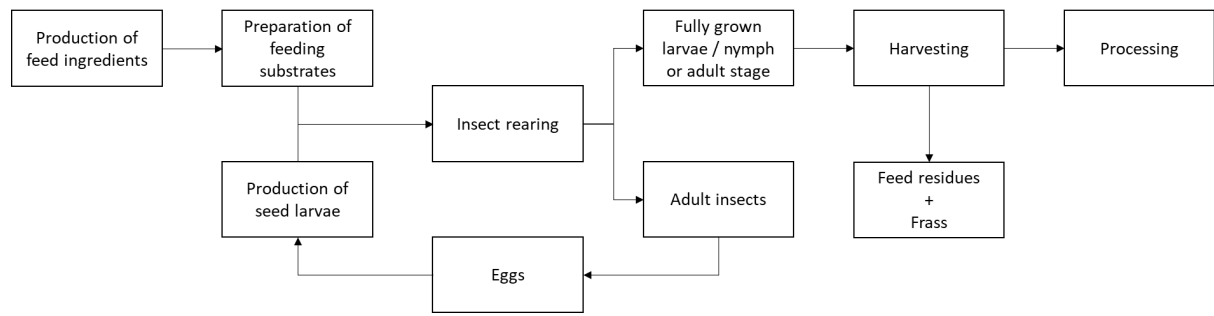


Figure I. Insect production system (Cortes Ortiz et al., 2016; IPIFF, 2022; Newton and Sheppard, 2012)

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.