Have the environmental benefits of insect farming been overstated? A critical review

Corentin Biteau[a], Tom Bry-Chevalier[b], Dustin Crummett[a]*, Katrina Loewy[a], Ren Ryba[c], Michael St. Jules[a]

[a]The Insect Institute, 2424 E York St. Unit 204, Philadelphia, PA 19125, United States

[b]Bureau d'Economie Théorique et Appliquée, University of Lorraine, Maison de la Recherche, 23 rue Baron Louis, 54000 Nancy, France

[c]Animal Ask, Unit 10, The Linen House, 253 Kilburn Lane, London W10 4BQ, United Kingdom

*Corresponding author: dustin@insectinstitute.org

Abstract

Humanity's food system has an immense environmental impact, and insects have been frequently proposed as a more environmentally sustainable option. The industrialised farming of insects for livestock feed and human food has attracted the attention of industry, policymakers, and the scientific community. However, many of the benefits commonly mentioned by companies and proponents of insect farming are challenged by current scientific evidence. This review examines the evidence used to assess insect farming's environmental benefits and drawbacks for both human food and animal feed. Significant knowledge gaps remain. Most studies have been conducted in small-scale settings, which may not accurately reflect real-world, industrial conditions. There are significant uncertainties, with many authors highlighting the fact that the future environmental impact of large-scale insect production is largely unknown. This is especially true given claims that insects can be fed on food waste and that insect frass can be used as fertiliser, both of which have considerable challenges to overcome at scale. Lastly, most insect based foods replace plant-based products with limited environmental impact rather than meat, and several studies indicate that insects-based feeds and pet food can have a larger environmental impact than conventional products. By providing a comprehensive overview, this review highlights key areas for further research and ensures policymakers have a clearer picture of the remaining uncertainties surrounding this emerging industry.

Keywords

black soldier fly; circular economy; cricket; insect farming; life cycle assessment; yellow mealworm

Contents

1. Introduction

The current food system significantly contributes to biodiversity loss, deforestation and climate change (Poore & Nemecek, 2018). Livestock farming plays a major role, occupying the vast majority of agricultural land but providing only a minority of the world's supply of calories and protein. Animal agriculture production is also responsible for a majority of the greenhouse gas emissions from the global food system (Xu *et al.*, 2021).

In contrast, insects are frequently cited as a more sustainable option than traditional livestock. While the industrialised farming of insects as food and feed is a new phenomenon, the practice of eating insects has a deep-rooted history and is practised by over two billion people globally (van Huis & FAO, 2013). The farming of insects as human food and animal feed has grown significantly in recent years, with increasing attention from industry, policymakers and the scientific community (Sogari *et al.*, 2022). The industry has gathered substantial investments (Montanari, Pinto de Moura & Miguel Cunha, 2021), and large-scale automated facilities farming trillions of insects have been constructed or are in construction. Favourable legislative changes in regions such as the European Union allow new uses of insects as human food and animal feed. Predominant species in insect farming include the yellow mealworm (*Tenebrio molitor* Linnaeus), black soldier fly larvae (BSFL; *Hermetia illucens* Linnaeus), and the house cricket (*Acheta domesticus* Linnaeus).

The overwhelming majority of investment in insect agriculture goes towards producing feed for aquaculture, pets, and livestock production, rather than food for humans. Insects as feed are positioned as a sustainable alternative to fishmeal and soy meal, which present environmental concerns. Pet food is currently the dominant market segment (50% in 2020), but aquaculture is projected to take the lead by 2030 (de Jong & Nikolik, 2021). Although insect-based human foods attract a minority of financial investment and remain niche in Western societies, producers seek to target consumers eager for new culinary experiences or concerned about their ecological footprint. Insects have positive nutritive qualities (Dobermann, Swift & Field, 2017), and common insect-derived products range from protein bars to pasta and even whole insects.

Insects convert feed into protein more efficiently than traditional livestock, with a lower feed conversion ratio (van Huis & FAO, 2013; Halloran *et al.*, 2016). Unlike mammals and birds, insects are cold-blooded, meaning they do not expend energy to regulate body temperature. Additionally, insects can, in principle, consume a variety of feed sources, including organic waste (Halloran *et al.*, 2016). However, these characteristics do not automatically make insect-based products environmentally friendly (Liverød, 2019; Lange & Nakamura, 2023). For instance, where insects eat feed-grade products and are then themselves used as feed, insect farming may increase the environmental footprint of our food system by introducing an additional step in the food production chain. More broadly, many factors influence the efficiency of insect production, including insect species, composition of the feed used for insects, production methods, and end use (Liverød, 2019; Berggren, Jansson & Low, 2019; Smetana, Spykman & Heinz, 2021b; Smetana *et al.*, 2023a).

Despite the promise of insect agriculture, large gaps in the literature remain. Most studies have been conducted in small-scale settings, which may not accurately reflect real-world, industrial conditions. Many of the studies have been conducted in developing countries with tropical climates, which means that two of the largest cost components of insect production—labour and energy demand—may be underestimated (Halloran *et al.*, 2017; Liverød, 2019; Thrastardottir, Olafsdottir & Thorarinsdottir, 2021; Niyonsaba *et al.*, 2023b, 2023a). Also, most papers focus on a specific sector, leaving some important gaps in the literature. Meanwhile, several studies point out significant uncertainties and highlight that the future environmental impact of large-scale insect production is "largely unknown" (Berggren *et al.*, 2019;

Lange & Nakamura, 2023). While the European Commission has recently approved new uses for insect products, its experts have also noted there is an "overwhelming lack of knowledge concerning almost every aspect of production" (EU Platform on Sustainable Finance, 2021). As a result, existing studies fail to provide a comprehensive understanding of insect farming's sustainability (Smetana *et al.*, 2023a).

In this article, we review the literature and critically examine the evidence that has been used to inform policy debates on the environmental impacts of insect agriculture. Firstly, we summarise the key drivers of the environmental impact of insect farming. Then, we critique the evidence on the environmental benefits and consequences of insects with reference to insect products' two main end uses: human food and animal feed. By providing a detailed overview of the scientific knowledge on the environmental impact of this emerging technology, we hope to identify key knowledge gaps for scientific research and to ensure that policymakers have a more comprehensive understanding of what questions remain.

2. Key drivers of the environmental impact of insect farming

The primary determinants of environmental impact in insect farming are the production of feed and the energy required for rearing and processing insects (Smetana, Schmitt & Mathys, 2019; Vauterin *et al.*, 2021). Risks to biosecurity and biodiversity are also relevant.

2.1. Feed

The feed provided to insects stands out as the most significant environmental factor (Oonincx & de Boer, 2012; Lundy & Parrella, 2015; Halloran *et al.*, 2016; Salomone *et al.*, 2017; Oonincx, 2021; Vauterin *et al.*, 2021; Sogari *et al.*, 2023b). By-products like organic waste usually yield better environmental outcomes than conventional feeds like grains (Halloran *et al.*, 2016; Smetana *et al.*, 2023a), although this is not always the option with the lowest environmental impact (Shockley & Dossey, 2014).

Several factors must be weighed, including the feed's nutritional content, cost, environmental footprint, the resulting growth rate of the insects, and whether the feed constitutes an unused side stream (Sogari *et al.*, 2023b). Generally, high-quality feeds like grains lead to faster growth cycles, but their production often results in a higher environmental impact, and their use may compete with use as human food or animal feed. On the other hand, lower-quality feeds like manure, household waste or potato peels typically result in a lower environmental footprint but can lead to smaller insects and extended growth periods, which might increase resource consumption during their growth phase and negate expected benefits (Smetana *et al.*, 2016, 2021b; Bosch *et al.*, 2019). For example, the yellow mealworm's growth cycle spans 26 days on high-quality feed compared to 103 days on dry, expired food (Ites *et al.*, 2020). The variability of organic waste complicates finding an optimal feed composition, and longer growth cycles can challenge the economic feasibility (Shurson, 2020).

Other elements also complicate the use of waste. Insects may experience increased mortality rates when fed with unprocessed waste. This has been observed in the most commonly farmed species, including crickets reared on municipal waste (Lundy & Parrella, 2015) and BSFL reared on manure (Miranda, Cammack & Tomberlin, 2020). The yellow mealworm is also not an ideal candidate for rearing on organic waste and manure substrates (Le Féon *et al.*, 2019; Harsányi *et al.*, 2020). Regulatory constraints in the European Union and the United Kingdom limit the use of most waste products as feed due to health and safety concerns following the outbreak of bovine spongiform encephalopathy (Salemdeeb *et al.*, 2017; Mancini *et al.*, 2022). Furthermore, since the nutritional profile of insect meal depends on the components of the insects' feed, waste-fed insects may be unable to deliver the stable, consistent nutritional content in the insect meal as demanded by aquaculture and livestock producers (Sogari *et al.*, 2023b).

As a result, most insect farming companies do not use organic waste and instead rely on high-quality, often grain-based substrates (Gibson, 2022; Faes, 2022). These substrates are already widely used as animal feed (Heidari *et al.*, 2021), meaning that insect agriculture usually competes with these established sectors. Separately, insects fed using organic waste could compete with anaerobic production, which also uses waste to produce biofuel, electricity, or heat (Thévenot *et al.*, 2018).

2.2. Heating

The most significant driver of direct energy consumption in insect farming is the heating needed for rearing and drying processes, which significantly contributes to the carbon footprint (van Zanten *et al.*, 2015; Salomone *et al.*, 2017; Thévenot *et al.*, 2018).

Insects are cold-blooded and rely on external heat sources to regulate their body warmth (Premalatha *et al.*, 2011). The commonly farmed insect species require stable temperatures year-round to thrive, and the optimal temperature range is around 29 to 31 degrees C at 50 to 70 percent humidity (Makkar *et al.*, 2014). Growth rates are temperature-dependent; for example, crickets complete a growth cycle in approximately eight weeks at 30°C, but this extends to eight months at 18°C (Ayieko *et al.*, 2015). Extended growth periods can lead to increased feed and water consumption while reducing the output from the system, thereby increasing environmental impacts (Halloran *et al.*, 2016; Liverød, 2019).

The geographical location significantly affects the energy needed for temperature control (Halloran *et al.*, 2016). Insects can be reared outdoors in tropical climates such as Thailand (Halloran *et al.*, 2017), but heated facilities are necessary in cooler climates such as in the EU or UK, increasing energy use (Liverød, 2019). Maintaining optimal temperatures year-round, especially during winter, requires substantial energy and contributes to greenhouse gas emissions, though using renewable energy sources or residual heat from nearby facilities can lessen this (Quang Tran, Van Doan & Stejskal, 2022). Given that temperature and energy mix vary by location, the findings of a study conducted in one context may not directly apply to another.

Another driver of energy consumption is insect drying (heat drying, solar drying, freeze-drying) (Salomone *et al.*, 2017; Roffeis *et al.*, 2017, 2020; Mertenat, Diener & Zurbrügg, 2019; Bava *et al.*, 2019; Ites *et al.*, 2020). Insect drying can have a "relatively high energy demand and could result in high associated environmental impacts" (Smetana *et al.*, 2021b).

Some other factors have a smaller influence on the environmental impact of insect production. The impact of transportation, feed processing and the reproduction module (where insects procreate) is comparatively minor (Smetana *et al.*, 2021b). The environmental cost of constructing the facility is often not assessed but is presumed to be marginal, although this conclusion is based on older studies that may not be representative of emerging industrial processes (Halloran *et al.*, 2016).

2.3. Biodiversity threats and invasive species

There are serious concerns about the ecological consequences of the release of farmed insects, in contexts where they are used both as food and feed. However, this topic is under-researched, and these risks are not included in LCAs (Halloran *et al.*, 2018; Moccia, 2022).

Farmed insects, if released into natural environments, could also pose risks by adversely affecting local insect populations. This issue pertains to the use of insects for both human consumption and animal feed. There is a risk that farmed insect species may escape, potentially disrupting local ecosystems through competition with native species or by introducing harmful genes into wild populations. Moreover, these insects could become vectors for novel pathogens and diseases. Research indicates that genes selected for in farms have been already transferred to wild BSFL populations in Europe (Generalovic *et al.*, 2023).

Some researchers express concern that, despite the controlled environment on insect farms, commercially farmed insect species can escape, establish in new environments, and “wreak havoc on the natural ecosystem” (Yen, 2015; Halloran *et al.*, 2018; Wilderspin & Halloran, 2018). For instance, such escapes could occur during natural disasters or other unforeseen events, as seen with pigs in the US during Hurricane Florence (Graff, 2018). An additional challenge with insects, unlike conventional livestock, is the near impossibility of recapture. Weissman et al. (2012) estimate that if any commercial cricket species are approved for import, we should “expect them to be introduced into the environment whether through accidental escape or intentional release”. This could displace local species (Food Standards Agency, 2023).

Past instances of invasive insect species include the Africanised bees, commonly known as “killer bees”, and the spongy moth. Africanized bees were brought to Brazil for a cross-breeding experiment with local honey bees to boost honey production (Smithsonian Institution, n.d.). However, in 1957, a mishap led to the escape of 26 selectively bred queen bees and their workers (Winston, 1992), resulting in their spread to other South American nations, Central America, Mexico, and the USA. Similarly, spongy moths (*Lymantria dispar dispar* Linnaeus) were brought to the USA by a single individual aiming to crossbreed them with silk moths for the silk industry (Doane & McManus, 1981). These moths have become a significant threat to North American forests, damaging trees through defoliation (USDA, n.d.). Their economic impact is substantial, with an estimated loss of approximately 120 million USD in residential property value annually in the US from 1998 to 2007, and federal expenses of 298 million USD targeted at controlling the spongy moth during the same period (Invasive Species Centre, 2019).

While some species, like the black soldier fly, were initially considered unlikely to establish in the wild (Spranghers *et al.*, 2017), more recent evidence arrived at the contrasting conclusion that they could indeed establish under certain conditions (Roháček & Hora, 2013; Jonsell, 2017). Experts reporting to the

European Commission highlight that these risks should not be discounted and that the precautionary principle should be exercised, especially given the short life spans and rapid rates of dispersal of these insects (EU Platform on Sustainable Finance, 2021, p. 23).

Furthermore, high-density insect farms expose insects to various diseases and pathogens, including novel strains (Weissman *et al.*, 2012; Jansson, Hunter & Berggren, 2019). This raises concerns about escaped insects transmitting these diseases to wild populations, especially pollinators, which are already facing numerous threats. The impact of diseases such as the densovirus that "devasted" the American cricket pet food industry highlights the potential risks to local biodiversity (Weissman *et al.*, 2012; Jansson *et al.*, 2019). In response to this disease, cricket producers' search for a virus-resistant cricket species inadvertently led to the distribution of a *Gryllus* species across Europe and the US, posing potential risks to native fauna and agriculture. Weissman et al. (2012) have recommended eliminating this new species to prevent its establishment in the US. It is also likely that destructive pathogens originating from commercial bees have been "spilling over into wild bee populations", contributing to the "devastating losses of honey bees throughout North America" (Otterstatter & Thomson, 2008).

The introduction of genetically modified insects, bred for enhanced size, strength, speed, adaptability, and resilience, could multiply concerns about invasive species (Moccia, 2022). Research is already underway to produce insects using genetic manipulation and selection (van Huis, 2022). Conversely, selectively bred species could have undesirable phenotypes that could lead to genetic pollution – the spread of contaminated altered genes to natural insect populations, potentially reducing their fitness (Ellstrand, 2001). This is a known problem in other types of animal agriculture, such as aquaculture, as seen in the escape of farmed fish and its detrimental impacts on wild fish populations. There are several cases where farmed salmon, mostly products of selective breeding (Janssen *et al.*, 2017a), reproduced with wild populations. This led to the transmission of altered genetic characteristics in wild populations, with lower life spans, reduced individual fitness, and increased vulnerability to diseases (Glover *et al.*, 2017; Faust *et al.*, 2018). Recent research has found evidence of genes selected for in domestic black soldier fly populations spreading into wild European populations, "likely as a product of escaped flies from commercial, or amateur farms" (Generalovic *et al.*, 2023). The result is the potentially undocumented loss of traits from wild populations via homogenisation.

In the context of Sweden, Jansson et al. (2019) recommend that insect species that do not exist locally should “not be used in production systems”, extending this caution to food and feed production. The precautionary principle suggests that industry should err on the side of not using non-native species unless there is robust scientific evidence to suggest that using any particular non-native species is indeed safe (Berggren *et al.*, 2019). This guideline would restrict the variety of species available for insect farming, potentially impacting producers' ability to select the most efficient species for their specific purposes. This additional limitation could increase the environmental impact of insect farming.

3. Environmental impacts of insects as human food

Currently, the insect food market attracts only a minimal share of the funding in the insect sector. According to a Rabobank report, "their market share is negligible, and opportunities, at least for now, are limited" (de Jong & Nikolik, 2021). Nevertheless, edible insects represent the most publicly visible segment of the sector, including in the mainstream media, shaping how the public thinks about insect farming.

For insect-based foods to be considered more sustainable than existing foods, they must have a lower environmental footprint than foods they aim to replace and compete with. Therefore, assessing the ecological impact of insects as food requires understanding what products insect foods are aiming to substitute.

Most scientific research on this topic compares insects to vertebrate meat (Smetana *et al.*, 2023a) and, to a lesser extent, meat alternatives (Hadi & Brightwell, 2021). This comparison is based on their similar protein content and the significant environmental impact of meat production, suggesting that substituting meat with insects could reduce ecological harm (van Huis & FAO, 2013).

However, this argument is based on the implicit assumption that insect products will only replace existing meat products. While insects aim to offer an additional source of protein, their adoption may not always result in reduced meat consumption (Halloran *et al.*, 2016). Due to consumer acceptance issues, many edible insects in Western countries are predominantly used in items such as snacks, which do not serve the same culinary role as meat. This presents an important consideration: if insects replace non-meat foods, what are the implications for sustainability?

3.1. What are insect-based foods competing with?

The most common insect-based products in Europe and North America are whole insects, energy bars, biscuits and cookies, snacks such as chips or crackers, protein powder, pasta, burger patties, or bread (Skrivervik, 2020; Mancini *et al.*, 2022; Żuk-Gołaszewska *et al.*, 2022; Sogari *et al.*, 2023a). The IPFF (2020a) estimated that whole insects constituted close to a quarter of the market, “followed by bars, snacks, speciality food ingredients [e.g. food supplements] and pasta” (Figure 1). Whole insects are mainly consumed as snacks and sometimes as condiments or ingredients (Halloran *et al.*, 2016; House, 2019).

Except for burger patties, insect food products do not fill the culinary role of meat as it is commonly consumed, e.g. chicken nuggets, bacon strips, veal cutlets or ham slices. Meat-like products only accounted for 8 percent of the insect food market in 2020, a figure expected to rise but remain below 12 percent by 2025 (IPIFF, 2020a). Instead, insects mostly replace traditionally plant-based products, like maize in tortilla chips or chickpea flour in protein-supplemented pasta or bread. These ingredients usually have a much lower environmental footprint than meat (Poore & Nemecek, 2018; Ritchie, Rosado & Roser, 2022).

Taking the European Union as an example, the European Commission has approved the inclusion of insects in various products, not all of which replace meat (EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA) *et al.*, 2021). Industry members have sought approval for insects in many vegetable-based dishes, meals, soups and salads (Mancini *et al.*, 2022). For instance, approvals sought include onion soup, beer, tortilla chips, potato-based dishes, hummus and tomato soup. Many of these products have lower environmental impacts than farmed insects (see below), so incorporating insects could increase rather than decrease the environmental impact of the food system.

Of the 45 food product types requested for which authorisation was sought, fewer than 10 have the potential to replace meat-based products. Even in these, insect ingredients included only part of the product. For example, "sausages, meatballs, and meat burgers were listed with an inclusion of approximately 30–40% [...] of frozen locusts, mealworms, and crickets, or approximately 10–16% [...] of dried/powdered insects," while imitation meats were limited to "50% of dried/powdered insects or 80% of frozen insects" (Mancini *et al.*, 2022). Moreover, even when they replace animal-sourced foods, insect-based products might compete with more sustainable plant proteins. For instance, insect protein powder could replace protein powder made from whey. However, plant-based protein supplements, which comprised nearly 40 percent of the market in 2023 and are expected to grow, may be a more sustainable alternative (Grand View Research, 2023).

Some companies put a higher focus on meat substitutes. The company Ÿnsect, for instance, sells products like "fibre textured insect protein", which is advertised as suitable for meat alternatives like patties, sausages, patés or loose minced meat (Ynsect, 2022). However, Ÿnsect also proposes using this product in baking and ice cream, and the company also suggests using some of their other products, such as the "whole mealworm powder", in snacks, cereals or pasta.

Producing insect-based bread, pasta, or crisps does not compete with meat; these products compete with conventional or supplemented bread, pasta or crisps (Sogari *et al.*, 2023a). If most insect-based products do not aim to replace established meat dishes, their contribution to reducing the environmental footprint of the food system might be limited and even detrimental. Instead, the public might consume these insect products in addition to meat, maintaining current meat consumption levels. Insects would primarily compete with plant products. Therefore, comparing the sustainability of insects with meat, as is commonly done in the literature (Smetana *et al.*, 2023a), does not provide a complete perspective. There is a risk of fostering a perception that insects are inherently sustainable, even when used in desserts and snacks, rather than specifically as meat replacements. On the other hand, some argue that these products may serve as a gateway, fostering acceptance for a broader, less processed range of insect-based foods. Introducing novel foods like insects in familiar contexts could potentially help create more positive expectations in the future (van Huis & Rumpold, 2023). However, this "gateway hypothesis" has not yet received empirical support (House, 2019). Another hypothesis is whether additional protein in the diet, from insects added to food like pasta, cookies, or protein bars, could lead to reduced meat consumption elsewhere in the diet. However, we have not encountered any evidence to support this claim. One study on found that fortified food consumption in Finland did not significantly alter nutrient intake, including meat consumption, between users and non-users (although the study was not limited to protein supplements) (Hirvonen et al., 2012).

[FIGURE 1 ABOUT HERE]

3.2. Consumer acceptance of different products

The industry's focus on incorporating insects into familiar processed products aims at increasing consumer acceptance (Mancini *et al.*, 2022; Żuk-Gołaszewska *et al.*, 2022). Studies indicate that Western consumers are less likely to consume unprocessed insects where parts like the head or the legs are visible (Schösler, de Boer & Boersema, 2012; Ruby, Rozin & Chan, 2015; Hartmann & Siegrist, 2017). One study concludes that "consumers are unwilling to accept the direct substitution of a 'nice' slice of meat with a 'strange' dish of insects" (Mancini *et al.*, 2022). Companies have concentrated on products that are most appealing to consumers. However, this inherently limits the range of meals that insect-based products can replace.

It remains uncertain whether acceptance of insect-based snacks will extend to meat-like products. When considering insect-based foods, consumers have preferred textural qualities such as crunchiness and firmness, found in snacks, over qualities like juiciness and softness, which are typical of meat products (Bisconsin-Júnior *et al.*, 2022). This preference suggests that insect-based meat alternatives might face more challenges in gaining acceptance than expected. In the literature examining consumer acceptance of insect-based foods, only a few studies have focused on products that could act as meat substitutes specifically. Most research assesses the overall acceptability of insect-based foods, often without making specific distinctions. Among studies that focused on specific products, the most commonly analysed products are burgers, bars, chips, biscuits, and bread, with only burgers representing a direct meat substitute (Mina, Peira & Bonadonna, 2023). For example, Lombardi et al. (2019) explored consumer willingness to pay for insect-based products, highlighting their environmental benefits compared to pork. However, the products in their study were cookies, pasta, and chocolate bars, not sausages. One survey found that "consumers were most willing to accept insects in snacks (37%), main dishes (26%) and desserts (23%), and they were least inclined to accept insect-based salads (7%), soups (6%) and unprocessed insects (1%)" (Caparros Megido *et al.*, 2014; cited by Żuk-Gołaszewska *et al.*, 2022). This implies that even if a study reports a moderate or high acceptance rate for insect consumption, it may not be indicative of all product types.

Young people are “most willing to consume insects if incorporated into energy bars, cereals, and sweet bakery products” according to Palmieri et al. (2023) (cited by Michel & Begho, 2023). However, this also means that meat-like insect products are not among the ones these consumers are most ready to try. More generally, the idea of a 'gateway dish', leading to broader acceptance, lacks empirical support. Past examples of new ingredients gaining in popularity, such as raw fish in sushi, tend to show that instead, many elements are required, such as skilled chefs, new recipes or cultural contexts in which to try the new ingredient (House, 2019). Consequently, it seems “unlikely” that insects will be popularised through a gateway dish, such as snacks or desserts.

This trend is supported by a study conducted by Michel et al. (2023) in the UK. In a survey, 248 consumers were presented with a choice between different types of sausages: pork-based, cricket-based, and hybrid varieties, each with a specified price. The findings revealed that insect-based sausages faced significant price penalties compared to pork-based products, meaning that most participants showed a lower willingness to pay for these products, preferring them only when priced lower than pork-based options. The price penalty, while varying, was significant across all consumer groups, including environmentally conscious individuals with low food neophobia, even after they were informed about health and environmental benefits.

3.3. Environmental impact of insects compared to non-meat products

One relevant question is whether adding insects to common plant-based foods, such as pasta or bread, constitutes a sustainable practice. Does this inclusion lead to a reduction or an increase in the environmental impacts of these foods? Surprisingly, there is a significant lack of research specifically addressing this issue. We found no studies directly answering this question, a notable research gap considering these products represent the vast majority of insect-based foods.

The closest relevant studies involve comparisons between insect-based foods and plant-based alternative proteins. The most comprehensive such study is the review by Smetana, Ristic, et al. (2023b), which compares various meat substitutes' environmental impacts. The study considers GHG emissions, land use, and energy use. According to this review, the range from most impactful to least impactful is as follows: beef, microalgae, cultured meat, poultry, insects, and plant-based meat substitutes. This ranking indicates that while insects have a lower environmental impact than many alternatives, they are outperformed by plant-based substitutes. Therefore, it is plausible to conclude that adding insects to plant-based products, such as tortilla chips, crackers, or vegetable-based dishes, could increase these products' environmental footprint, especially if the dishes are otherwise not highly processed.

However, in scenarios where insects are used as a substitute for protein-enhanced products (e.g., fortified bread instead of conventional bread), the environmental impact would depend on what the consumers would have chosen otherwise. For instance, consider the cricket-based bread sold by the Finnish bakery chain Fazer (Reuters, 2017). If, in the absence of this insect-based alternative, consumers had opted for conventional bread instead, purchasing the insect product would likely result in a higher environmental footprint since insect production has a greater impact on the environment than wheat production. This consideration extends to a range of products authorised in the EU, including legume-based dishes, snacks (e.g., tortilla chips, crackers), cookies, chocolate, soups (e.g., onion, tomato), salads, beer, potato-based dishes, and hummus.

There are cases where consumers might choose other fortified products in the absence of insect alternatives. Such products include protein bars, protein powder, and fortified pasta or bread.

Supplemented foods can acquire protein from a range of products. For instance, supplemented pasta can be fortified with whey protein but also with soybean, pea, bean or chickpea flour (Messia *et al.*, 2021). In that case, the environmental outcome depends on the protein source being replaced. Insect proteins replacing animal-derived proteins, such as whey from cow's milk, generally result in a lower environmental footprint (Smetana *et al.*, 2019). Conversely, when insects substitute for plant-based proteins like those derived from peas or soybeans, they tend to increase the environmental footprint. Plant-based protein supplements constitute nearly 40% of the market (Grand View Research, 2023).

3.4. Environmental impact of insects compared to meat products

When insects are used as meat substitutes, their environmental impact generally appears more favourable than that of meat, although this is not guaranteed. This advantage is partly due to insects' high efficiency in converting feed into protein. On average, studies tend to show that the production of insects for human consumption is less damaging to the environment than meat production, but not for all environmental impacts. The most recent review of the topic is by Smetana et al. (2023a) (Figure 2). It relied on the Sustainability Assessment of Food and Agriculture Systems the FAO, which serves as a universal benchmark to evaluate sustainability across the food chain. When comparing the environmental impact of insect farming with conventional meat production, several key aspects emerge (Figure 2) (Smetana *et al.*, 2023a):

- ***Greenhouse gas emissions***: Insect farming generally results in lower GHG emissions compared to traditional meat products. In the beneficial scenarios considered by Smetana et al., the authors estimate that emissions from insect farming range from 0.3 to 3 kg CO2eq per kilogram of insect biomass (from the least to most intensive production scenarios). This is significantly lower than beef, which emits around 35.0 kg CO_2eq per kg. In the study of Smetana et al., pork and poultry have emissions of 6.95 and 5.97 kg CO_2eq per kg, respectively.

- ***Land use***: Insect farming tends to require less land, which is also beneficial for biodiversity. The authors estimate that "sustainable" methods of insect farming in Europe tend to occupy between 0.36–3.6 m^2 per kilogram of insect biomass. This is less than the land required for producing beef (23.1 m^2/kg), pork (6.28 m^2/kg), or poultry (4.64 m^2/kg).
- ***Energy use:*** The energy consumption for insect farming is also generally lower. Smetana et al. estimate that non-renewable energy use in the most efficient insect farming methods in Europe ranges from 0.36 to 21.2 MJ per kilogram of insect. In comparison, beef, pork, and poultry consume about 104.0, 28.3, and 23.8 MJ of non-renewable energy per kilogram, respectively.
- ***Water use:*** Perhaps surprisingly, the water footprint of insects seems higher than that of conventional meat products. Smetana et al. estimate a range of 0.4–0.8 m^3 of water per kilogram of insect, based on lower impact estimates. This is higher than the average water footprint of beef (0.25 m^3/kg), pork (0.05 m^3/kg), and poultry (0.067 m^3/kg). Initial studies have indicated a lower water footprint for insects (Oonincx & de Boer, 2012; Shockley & Dossey, 2014), but recent findings challenge this view. The substrate was the most significant driver for water use, followed by facility hygiene and maintenance (Quang Tran *et al.*, 2022).

[FIGURE 2 ABOUT HERE]

Overall, insect farming shows promising results in reducing GHG emissions, land use and energy use when compared to conventional livestock (Oonincx, 2021; Vauterin *et al.*, 2021). However, they also point out that in some cases, insects can have a higher environmental impact on some metrics compared to chicken, although results are not necessarily consistent between studies.

Regarding water usage, the methodologies used in different studies vary, making direct comparisons with meat substitutes challenging (Smetana *et al.*, 2023b). However, when comparing insects to compound feed—a mix of plant-based protein sources commonly used in conventional animal feed such as soy, maize, and wheat—studies suggest that insects have a significantly larger water footprint (0.4–0.8 m^3 of water per kilogram of insect, compared to 0.0179 m^3) (Smetana *et al.*, 2023a). Thus, insects tend to have a higher water usage than plant sources.

The feed conversion ratio (FCR) is also a common indicator for assessing the efficiency of insect feeding and growing. The FCR represents the quantity of feed required to produce one kilogram of insect mass. For instance, an FCR of 2 for mealworms means that 2 kg of feed is needed to produce 1 kg of mealworms (Thévenot *et al.*, 2018). All else being equal, a lower FCR indicates a more efficient system. This measure has limitations, such as not accounting for digestibility, focusing on economic efficiency more than resource efficiency, and using varying calculation methods across studies (Halloran *et al.*, 2016; Smetana *et al.*, 2021b).

That said, insects generally have a lower FCR than conventional livestock (Table 1). Depending on the species, insects can more efficiently convert feed into body mass than conventional livestock can, except for fish and chicken (Oonincx *et al.*, 2015; Jansson *et al.*, 2019). When considering edible weight, insects have a further advantage because of their higher edible content, up to 80 percent for crickets, compared to 40 percent in cattle and 55 percent in pigs and chickens. However, there is still a protein loss compared to eating plants directly (Bashi *et al.*, 2019). This extra step can be justified if the insects consume waste that absolutely cannot otherwise be used (the use of food waste as substrate is discussed further below).

[TABLE 1 ABOUT HERE]

3.5. Comparison with alternative proteins

Efforts to reduce the substantial environmental impact of the modern food system have led to exploring various alternatives, including insect-based foods and other protein sources. This latter group of alternatives includes plant-based meat substitutes, cultured meat, and proteins obtained through fermentation processes like single-cell proteins. Their goal is to replicate the sensory and nutritional properties of meat while minimising environmental impacts. As mentioned earlier, the latest comprehensive review assessing the environmental impacts of different meat substitutes is the study by Smetana, Ristic, et al. (2023b), covering categories such as GHG emissions, land use, and energy consumption. This study concluded that, when evaluated on a per-protein basis, the impact of these food sources ranges from highest to lowest as follows: beef, microalgae, cultured meat, poultry, insects, and plant-based products. Insects generally exhibit a lower environmental impact compared to most other alternatives, but are outperformed by plant-based substitutes.

However, direct comparisons between alternative proteins and insect-based options are rare. Data scarcity, particularly regarding the environmental effects of microbial protein, lab-grown meat, pea protein, and nuts, makes these comparisons challenging (Smetana *et al.*, 2023b). The water footprint, for instance, displays widely different results due to varying methodologies. Different substitutes display significant variations, with more processed products having more impact. Moreover, few studies detail the impacts of insect-based meat substitutes. For instance, some studies assume that "fresh" insect biomass is equivalent to raw meat, suggesting greenhouse gas emissions ranging from 3.9 to 29 kg CO_2eq per kg of protein for raw insect biomass (Upcraft *et al.*, 2021). Other studies consider more processed products that mimic meat texture (Smetana *et al.*, 2023b).

One of the few studies in this area compared the environmental impact of burgers made from different meat substitutes, including insects, pea-based, mycoprotein, and soy-based products (Smetana *et al.*, 2021a). This study found that all of these substitutes were five to six times more sustainable than beef patties, reducing environmental impacts by at least 80 percent. Insect-based and soy-based products performed the best across a range of environmental impacts.

Smetana, Ristic, et al. (2023b) also explored the impacts of hybrid meat substitutes. More processed insect-based products, such as burgers, require combining with other ingredients like plant flours, protein, fibres, spices, or even meat to achieve the desired texture. For instance, Frankfurt sausages can be formulated with a blend of pork meat and 10 percent yellow mealworm (Choi *et al.*, 2017). Another study reported that 40 percent of pork meat could be replaced in meat emulsion systems (Kim *et al.*, 2020). This aligns with EU regulations, which stipulate that "meat imitates" can include a maximum of "50% of dried/powdered insects or 80% of frozen insects" (Mancini *et al.*, 2022). In products like burgers and sausages, the inclusion rates for insects drop to 10 percent for dried/powdered and 40 percent for frozen. These hybrid products only partially replace meat with insects. While more familiar to consumers, their environmental impact is higher than that of meatless products, especially at low inclusion rates like 10 percent. Plant-insect hybrids could offer a more environmentally friendly option than plant-meat and insect-meat hybrids.

Furthermore, when evaluating different meat substitutes, environmental and health impacts should not be the sole consideration; social and economic factors like cost-competitiveness and scalability are also crucial dimensions of sustainability. Any particular substitute needs to be able to be produced on an industrial scale while maintaining its environmental benefits. However, "the degree of technological and social-institutional change required for meat alternatives is highest for [...] insects", as well as cultured meat and algae, more so than for plant-based meat substitutes (Figure 3) (van der Weele *et al.*, 2019; van Huis, 2022). For instance, upscaling insect production requires regulatory changes at an institutional level to allow, e.g., the use of waste products as substrates, as well as technological changes to ensure high-quality production (van der Weele *et al.*, 2019; Niyonsaba *et al.*, 2023b). Insects have a lower consumer acceptance than all other meat substitutes (Onwezen *et al.*, 2021).

[FIGURE 3 ABOUT HERE]

3.6. Zoonotic diseases and antibiotic use

The literature suggests that, compared to birds and mammals, edible insects present a relatively low risk of transmitting zoonotic diseases to humans, primarily due to significant taxonomic differences between insects and humans (Lange & Nakamura, 2021; Doi, Gałęcki & Mulia, 2021; Gałęcki, Bakuła & Gołaszewski, 2023). Most microorganisms specific to insects are not major contributors to zoonoses (Doi *et al.*, 2021), exemplified by the small number of reported pathogens detected in the black soldier fly (Joosten *et al.*, 2020; van Huis, 2022). Furthermore, the controlled conditions of insect farming help reduce pathogen spread (Faes, 2022). There are significant health concerns caused by conventional livestock that insects could help mitigate if consumed as a meat replacement (Doi *et al.*, 2021). On the other hand, a lack of reported pathogens may be due to low research effort rather than a genuine lack of pathogens, as recent scientific studies and anecdotal evidence from scientists working with black soldier flies support the notion that the number of pathogens may be higher than originally thought (InsectDoctors, 2023; She *et al.*, 2023).

Nevertheless, insects are not completely free from pathogens that could impact human health (Berggren *et al.*, 2019). At least one study has suggested that viruses associated with insect production could pose a risk to both human health and animal health (Bertola & Mutinelli, 2021). Insects can be the “primary or intermediate hosts or carriers of human diseases” (Marshall, Dickson & Nguyen, 2016; see also Jansson *et al.*, 2019; Faes, 2022). For example, mealworms have been identified as a potential disease vector in poultry (Rumbos *et al.*, 2019). While viruses pathogenic in vertebrates cannot replicate in insects, they can still transmit them passively, acting as a vector (Doi *et al.*, 2021). As the microbiological safety of edible insects is still under debate (Gałęcki *et al.*, 2023), appropriate sanitary and biosecurity rules should be applied (Doi *et al.*, 2021). The potential for insects to transmit harmful pathogens to humans has not been explored sufficiently and requires further investigation (Berggren *et al.*, 2019; Lange & Nakamura, 2021; Bertola & Mutinelli, 2021).

Furthermore, edible insects are an "underestimated reservoir of human and animal parasites" and potentially "the most important parasite vector for domestic insectivorous animals" (Gałęcki & Sokół, 2019). A study of small-scale insect farms for pet food found parasites in over 80% of them. In 30% and 35% of these farms, these parasites had the potential to affect humans and animals, respectively. These parasites can play a role in the dispersion of invasive diseases (van der Fels-Klerx *et al.*, 2018; Doi *et al.*, 2021; Gałęcki *et al.*, 2023).

The use of antibiotics in insect farming and its impact on antimicrobial resistance remains uncertain. Pathogen outbreaks can devastate insect populations, posing production risks (Taponen, 2015; van Huis, 2022). In the event of diseases, entire insect populations in farms may need to be eradicated. The future of disease management in insect farming remains uncertain (Maciel-Vergara & Ros, 2017; Berggren *et al.*, 2019), although in a recent survey of industry stakeholders, this issue is "considered of medium concern relative to other 'operational' barriers" (Niyonsaba *et al.*, 2023b). Antibiotics could be used, but it is unclear whether this would be effective or desirable, considering the risk of antimicrobial resistance (Suckling *et al.*, 2020). Initial antibiotic use in insect farming was initially low (Halloran *et al.*, 2016), and the industry claims that they are not used (IPIFF, 2020b), which could help mitigate antimicrobial resistance risks if insects act as meat substitutes.

However, it remains unclear whether this is likely to remain this way. Intensive farming of insects might face similar pressures as other animal farming industries, where intensification is a key factor in disease emergence (Slingenbergh *et al.*, 2004; Jones *et al.*, 2013; Lange & Nakamura, 2021). Blanket treatments in response to disease often lead to trends like antimicrobial resistance, reducing the effectiveness of antimicrobials over time. This scenario is evidenced in diverse animal farming industries, such as pigs or salmon, where novel zoonoses emerge and antimicrobial resistance arises. The use of antibiotics is frequent even in shrimps, another arthropod group (Holmström *et al.*, 2003; Halloran *et al.*, 2016), and in silkworms, one of the most commonly farmed insects (Li *et al.*, 2020). Some studies indicate that insects represent a reservoir for antibiotic-resistant bacteria (Zurek & Ghosh, 2014; van der Fels-Klerx *et al.*, 2018). As mentioned by the British Food Standards Agency (2023), "there is a potential hazard that the rearing of edible insects on a large scale may incur the use of antibiotics [...], contributing to AMR. The exact impact of this practice is not possible to determine with the available information."

3.7. Potential rebound effects

The impact of promoting insect consumption on other environmentally conscious behaviours remains an open question. Some studies suggest that encouraging "green" actions such as insect consumption can lead to unintended behavioural effects. For example, the moral licensing phenomenon involves people justifying less environmentally friendly actions due to their past positive behaviour (Burger, Schuler & Eberling, 2022). Encouraging such individuals to consume insects might inadvertently diminish their willingness to engage in other environmentally beneficial actions. Similarly, labelling insect-based products as "sustainable" might trigger the “negative footprint illusion” (Gorissen & Weijters, 2016; Holmgren, Andersson & Sörqvist, 2018; Threadgold *et al.*, 2021; Sörqvist & Holmgren, 2022). This illusion may lead consumers to believe that purchasing these "green" products does not add to their environmental footprint, potentially causing an increase in their overall consumption of these products. This effect was observed in the case of insect burgers (Kusch & Fiebelkorn, 2019). However, given the complexity of consumer behaviour, further research is specifically needed on insects to understand these implications.

3.8. Major knowledge gaps

When evaluating the environmental impact of insect farming, it is essential to acknowledge the limitations and gaps in existing literature. Such research is usually performed in a life cycle analysis (LCA), a method to quantify the environmental impacts of a product throughout its entire life cycle.

Consider crickets, one of the species most commonly reared for food (Table 2). For these species, we found no reliable impact estimate in Europe or other industrialised, Western countries. The first LCA by Halloran et al. (2017) indicated lower GHG emissions for crickets compared to meat, and this finding has been extensively cited. For instance, Hadi and Brightwell (2021) referenced this study when comparing the environmental impacts of insects, plant-based, and cellular meat. However, Halloran et al. 2017 researched a medium-sized farm in Thailand. This study's context – crickets in an outdoor setting with tropical temperatures, fed on grain supplemented with pumpkins – significantly differs from potential farming conditions in Western countries, where indoor heating is often necessary due to cooler climates. Suckling et al. (2020), the first commercial-scale insect LCA in the UK, revealed considerably higher GHG emissions, primarily due to the need for constant heating. Their findings showed emissions nearly ten times higher than Halloran et al. 2017 and almost double those of broiler chickens fed soybean meal (with GHG emissions of 33.49 kg CO_2-eq per kg of protein, compared to 4.2 kg CO_2-eq in Halloran 2017 and 18 kg CO_2-eq for broiler chicken in the EU) (data from Vauterin *et al.*, 2021).

The Suckling et al. 2020 study, although more representative of UK conditions, was not wholly indicative of insect farming for human consumption. That study focused on the live pet food market, rather than the market for human consumption. The study also included the application of insect frass to the land, which displaced mineral fertilisers but increased carbon emissions. Additionally, it provided data for the cricket species *G. bimaculatus* but not for *A. domesticus*, the species more commonly farmed for human consumption. Consequently, there is no LCA specific to crickets as human food in the European context.

Given the wide gap in results, assessing how the average cricket farm will perform is challenging and needed.

This situation underscores the current data gap in understanding the environmental impacts of insect farming. Compared to well-established agricultural sectors, data availability for insect agriculture is lacking—this is especially true as producers often do not make their data public (Bosch *et al.*, 2019; Ites *et al.*, 2020; cited by Smetana *et al.*, 2021a). As of 2021, only four insect-related LCAs have been conducted on actual farms in Europe, including Suckling et al. 2020, with an additional two on pilot farms (Vauterin *et al.*, 2021).

This means that the scientific understanding of the environmental impacts of insect agriculture inherently relies on a small set of studies. Older studies, such as those by van Huis et al. (2013) and Smetana et al. (2016), are often referenced, but these may be outdated given the latest developments in this rapidly evolving field. The most cited LCA in the field, Oonincx and de Boer (2012), was based on a production system that is not representative of large-scale operations, with insects fed with fresh carrots and mixed grains and mostly used to produce live or frozen insects for birds or reptiles.

Most studies have been conducted in pilot or small-scale facilities, processing only 0.02 to 1 ton of dried insect biomass daily, which adds further uncertainty regarding their applicability to larger-scale commercial production (Smetana *et al.*, 2019). Initial studies showed promising results, but studies on larger-scale production reported less optimistic figures (Dobermann *et al.*, 2017). Some studies propose future scenarios with potential improvements, but they should be interpreted with extreme caution as they often contain unsupported assumptions (Oonincx, 2021). Such assumptions include factors such as the extent to which frass would effectively substitute organic fertiliser, the adoption of renewable energy practices, and the prospective utilisation of waste in the future (discussed below).

[TABLE 2 ABOUT HERE]

4. Environmental impacts of insects as animal feed

Insects as animal feed constitute the vast majority of the industry's funding (de Jong & Nikolik, 2021). In the following section, we examine the environmental impacts of insects compared to conventional feed products, focusing first on the pet food market and then on the broader animal feed market, which includes aquaculture and chicken feed.

4.1. Pet food: Environmental impacts of insects compared to conventional pet food

The pet food sector currently represents the largest market for insect proteins, accounting for about 50 percent of the total market for insects farmed as food and feed (de Jong & Nikolik, 2021; Sogari *et al.*, 2023b). Ÿnsect, an industry leader in Europe, has recently shifted its focus away from feed for fish and livestock production, focusing more on products like pet food due to profitability concerns (Byrne, 2023).

Given its large size, minimising environmental impact is a critical concern in the pet food market. Despite its significance, we found only one study that had extensively explored the environmental aspects of insect-based pet food production. Several sustainability claims originate from the industry instead. Beynen (2018) reviewed 12 insect-based pet foods and found that “eight included a claim that insects are a sustainable protein source”. Typically, the benchmark against which insect proteins were compared was human-grade meat.

However, conventional protein sources in pet foods are often not human-grade meat but meat co-products like meat meals, organs, bones, feathers, and fat (Pet Food Institute, 2020; Alexander *et al.*, 2020). These co-products have a comparatively low environmental impact and are similar to the food waste some proposed insects could feed on. This makes pet food production “more sustainable than many human food processing industries in terms of cropland, energy, and water usage" (Acuff *et al.*, 2021). If insect meal is incorporated into pet food, it is likely to replace these meat co-products, which are not farmed explicitly for this purpose. Some studies suggest that pet food has a high environmental impact (Okin, 2017; Su, Martens & Enders-Slegers, 2018). However, these studies often incorrectly assume meat is the primary protein source and "do not provide reference data on the impact of these conventional pet food ingredients", complicating direct comparisons (Bosch & Swanson, 2021).

Research dedicated to comparing insect-based and traditional pet food is sparse. Bosch and Swanson (2021) conducted the only study we found focused exclusively on this subject. Duijnisveld & Myriam (2022) include a relevant section but compare insects with meat rather than with meat co-products. Other studies briefly mention the potential of insects in pet food but lack detailed analysis. Acuff et al. (2021) compare a range of pet food ingredients, showing that most have a lower environmental footprint than insects, mainly animal by-products.

Bosch and Swanson (2021) concluded that, on average, insect proteins for pet food emit two to ten times more GHG than conventional sources. They refer to a Blonk Consultants report, which estimates the carbon footprint of pet food at "about 1 kg CO_2-equivalents per kg protein for a mixed meal and 2 kg per kg protein for a poultry meal" (Koukouna & Broekema, 2017). In comparison, emissions from insect production are higher, ranging from 3.9 to 7 kg of CO_2eq per kg of protein (Halloran *et al.*, 2017; Bosch *et al.*, 2019). Using manure as feed can potentially lower these emissions to between 1 and 7 kg CO_2eq per kg of protein (Bosch *et al.*, 2019). However, emissions can range from 15–29 kg CO_2eq per kg of protein in less optimised insect production systems (Ulmer, Smetana & Heinz, 2020).

An interesting case in France involved the company Tomojo, which faced scrutiny over its marketing claims about the environmental benefits of its pet food. The company advertised its products with assertions such as "Sustainable proteins approved by the planet" and "For an ecological... diet," comparing the impact of insects with beef production rather than with co-products. A complaint led to an investigation by the French Advertising Standards Jury (Jury de Déontologie Publicitaire, 2021), which deemed the claims unjustified and misleading (2021).

Additionally, comparing insects with other alternatives is essential. Plant-based pet foods have a lower carbon footprint than animal-based ones (Acuff *et al.*, 2021). The vegan pet food market, valued at $8.6 billion in 2021, is growing and is projected to reach $15 billion by 2028 (The Insight Partners, n.d.). Regarding health and palatability, while there are numerous methodological limitations with the existing literature, the latest systematic review found that plant-based pet foods are comparable, or perhaps slightly more advantageous, for the health of pet dogs and cats (Domínguez-Oliva *et al.*, 2023). However, a cautious approach is warranted, as further validation and controlled clinical trials are required (Davies, 2022). Important uncertainties remain, but the same is more true for insect diets; data on the nutritional quality of insects is less well-documented, with limited available data (Bosch *et al.*, 2014; McCusker *et al.*, 2014; Mouithys-Mickalad *et al.*, 2020; Acuff *et al.*, 2021).

4.2. Animal feed: Environmental impacts of insects compared to conventional fish and livestock feed

The use of insects as feed in animal agriculture is a growing practice that is expected to account for a significant portion of the insect market in the coming years. Insects as feed have often been promoted as having the potential to enhance the food system's sustainability, offering environmental benefits over traditional alternatives (van Huis & FAO, 2013). Assessing the validity of this claim requires an analysis of their ecological impact.

Using insects as animal feed can add an extra trophic level to food production. This creates a high "trophic pyramid" characterised by wasted energy: crops, including coproducts, are farmed and processed, then fed to insects, which are farmed and processed, and then fed to fish or chickens, which are then farmed and processed, to be eaten by humans. This is a less efficient process than using the feeds directly for farm animals or humans (Roffeis *et al.*, 2020).

4.2.1. Projections of insects as animal feed

Aquaculture is projected to account for 40 percent of the insect protein market by 2030 (de Jong & Nikolik, 2021). This would constitute less than one percent of the current global aquafeed market. The chicken feed market, encompassing broilers and laying hens, is estimated to make up about 25 percent of the insect feed market (de Jong & Nikolik, 2021). Pig feed is projected to be a fairly small part of the market (de Jong & Nikolik, 2021). We will not delve into the impact of feeding insects to ruminants like cows or sheep, as they are not anticipated to form a significant market segment in the near future (IPIFF, 2021). Additionally, while incorporating insects in ruminant diets might reduce methane emissions, there is a lack of detailed studies on their environmental impacts, and knowledge about the optimal composition and inclusion levels for ruminants remains limited (Renna *et al.*, 2023).

The most commonly used insect species for feed production include the BSFL, the yellow mealworm, and, to a lesser extent, the common housefly (van Huis, 2022; Gasco *et al.*, 2023). The BSFL is versatile and can be fed with a wide range of wastes, while the yellow mealworm's potential for using waste as feed is more restricted (Le Féon *et al.*, 2019; Harsányi *et al.*, 2020; Quang Tran *et al.*, 2022; Faes, 2022).

It is crucial to note that due to nutritional limitations, insect meal can only replace a fraction of conventional animal feed, not the entirety (Gasco *et al.*, 2023). Recommended inclusion levels of insect feed are up to 25 to 30 percent for fishmeal and up to 10 percent for broiler chicken and pig meal. Exceeding these limits can lead to reduced protein digestibility, with uncertainties about the health and welfare of pigs and chickens (Gasco *et al.*, 2023). Research on inclusion rates for shrimp feed (10 to 30 percent) is ongoing. Consequently, using insects as feed will not dramatically alter the environmental impacts of 70 to 75 percent of fish feed, and up to 90 percent of broiler chicken and pig feed. While replacing 10 to 30 percent of feed with insects could still yield positive outcomes, it is important to view insects as a supplementary source alongside traditional feeds.

4.2.2. Insect diet as the primary driver of environmental impact

The formulation of feed fed to insects during insect meal production must be precisely formulated in order to maximise the growth rates of the farmed animals to which the resulting, processed insect meal is fed. The insect diet involves considering a long and nuanced list of interacting factors, such as: "insect species and composition, processing method, availability and consistency of supply, nutrient digestibility, anti-nutritional factors, physical pellet properties, palatability, stability, safety, costs, impact on product quality, and legislation" (Gasco *et al.*, 2023). Producing insect meals as animal feed requires balancing a complex set of constraints influencing sustainability.

On one hand, high-quality substrates like soybean or rye meal can lead to higher insect yields but also increase environmental impacts. On the other hand, lower-quality feeds, such as certain types of waste (e.g. expired foods, potato peels), may result in slower insect yield and lower efficiency, extending the period required to grow and increasing resource consumption during this stage (Smetana *et al.*, 2016; Ites *et al.*, 2020; Smetana, 2023). Cost considerations heavily influence substrate choice, as slower growth rates can hinder economic viability. Due to legal, logistical, economic, and social challenges, the largest companies predominantly use high-quality commercial feeds or coproducts as substrates (IPIFF, 2018).

4.2.3. Environmental impacts of insect meal compared to compound feed

It is essential to keep in mind the limitations present in the existing literature, including the small scale of studies, methodological differences, and a focus varying between the use of insects as food, feed, or waste management solutions. The reported environmental impacts can vary significantly, sometimes tenfold or even a hundredfold, depending on species, substrates, energy sources, and geographical location (Liverød, 2019). Likewise, environmental impact estimates for conventional feed also vary.

As with insects for human consumption, the most recent comprehensive review on the environmental impacts of insect production for animal feed is by Smetana, Bhatia et al. (2023a) (Figure 4). This study compares the impacts of insect meal versus compound feed—a blend of various ingredients, including cereals, oilseeds, and additives. For context, in Europe, the primary protein constituents of compound feed are soybean meals (29%) and maize (12%), followed by wheat (10%) and rapeseed meals (9%) (FEFAC, 2021).

GHG emissions from insect farming for livestock feed vary significantly. Smetana, Bhatia et al. (2023a) report figures from 0.3 to 3 kg CO_2eq per kilogram of insect biomass, from the least to the most emissive production scenarios. In contrast, 1 kg of compound feed produces about 1.34 kg CO_2eq emissions. In some systems, using insects as feed can lower GHG emissions compared to conventional compound feed. However, in other cases, they appear to have a greater carbon footprint (Smetana *et al.*, 2023a).

A standard diet using commercial or proprietary substrate is estimated to produce around 2.3–3.1 kg CO_2eq per kg of fresh insects (Oonincx & de Boer, 2012; Halloran *et al.*, 2017). For dried larvae, emissions are about 5.76 kg CO_2eq per kg (Bava *et al.*, 2019), and emissions per kg of protein range from 3.9–7 kg CO_2eq (Halloran *et al.*, 2017; Bosch *et al.*, 2019). Less optimised production systems exhibit higher impacts, with emissions reaching up to 21.1 kg CO_2eq for fresh larvae (Suckling *et al.*, 2020) and 15–29 kg CO_2eq per kg of protein (Ulmer *et al.*, 2020).

The use of food waste as feed can result in emissions ranging from a beneficial -6.42 to 5.3 kg CO_2eq (Thévenot *et al.*, 2018; Smetana *et al.*, 2019; Bosch *et al.*, 2019; Ites *et al.*, 2020). The negative value (-6.42) indicates scenarios where insects help avoid the need for more costly waste treatment methods. Typically, waste is managed through processes like landfilling or incineration, each carrying some environmental impacts. However, when insects are used to process waste, they reduce the necessity for these treatments and their related environmental impacts. This also extends to land and energy use. While using manure as feed for insects offers potential environmental benefits, the impacts vary widely, ranging from 0.77-12 kg CO_2eq per kg of dried insects (Roffeis *et al.*, 2017) to 1-7 kg CO_2eq per kg of proteins (Bosch *et al.*, 2019). Nevertheless, the use of waste as a substrate may be constrained by several limitations, such as lower growth rates and regulatory challenges in the EU and the US regarding safety and possible contamination risks.

Data on the effects of insect farming for feed on land use and biodiversity also present a mixed picture. Land use for insect production is estimated at around 3.6 m² per kilogram of fresh insects (Oonincx & de Boer, 2012) to 94.7 m² per kilogram of dry insect weight (Bava *et al.*, 2019). When measured per kilogram of protein, the range is 1.1–93 m² (Bosch *et al.*, 2019; Ulmer *et al.*, 2020). Utilising by-products and waste for insect feed generally results in a lower, though still variable, footprint, such as 1.6 m² per kilogram of fresh insects (Thévenot *et al.*, 2018). These figures fluctuate between -16.8 and 7.7 m² per kilogram of dry weight (Roffeis *et al.*, 2015; Smetana *et al.*, 2019; Bava *et al.*, 2019; Ites *et al.*, 2020), and 0–1 m² per kilogram of protein (Bosch *et al.*, 2019). The negative value (-16.8) reflects cases where insects avoid costly waste treatment processes. It is worth adding that although many studies represent biodiversity impacts with the land use indicator, newer biodiversity assessment methods are emerging.

Smetana, Bhatia et al. (2023a) estimated that sustainable insect farming in Europe could have a land use impact ranging from 0.36 to 3.6 m² per kilogram of insects, reflecting the tenfold range observed in various studies. In comparison, producing 1 kilogram of compound feed requires 1.48 m² of land. Thus, if insect meal falls within the lower range of land use impact, it could yield positive environmental outcomes. However, if the land use for insect farming is on the higher side, it might lead to greater environmental impacts compared to conventional feed.

Regarding energy use, studies also show mixed results. Smetana, Bhatia et al. (2023a) focused on non-renewable energy use. Energy use for insect farming significantly depends on the substrate (Smetana *et al.*, 2021b). Conventional grain-based diets result in an energy expenditure of 33.7 MJ per kilogram of fresh insects (Oonincx & de Boer, 2012) and range between 159–425 MJ for each kilogram of protein (Bosch *et al.*, 2019; Ulmer *et al.*, 2020). Rearing insects on by-products and waste shows a wide range of energy use, from -108 to 62.8 MJ per kilogram of dry insect weight (Roffeis *et al.*, 2017; Thévenot *et al.*, 2018; Ites *et al.*, 2020) or 18–77 MJ per kilogram of protein (Bosch *et al.*, 2019).

Based on the most efficient insect farming methods in Europe, Smetana, Bhatia et al. (2023a) estimate that energy consumption ranges from 0.36 to 21.2 MJ per kilogram of insect. In comparison, producing a kilogram of compound feed requires about 5.81 MJ. Although the most efficient insect farming methods could substantially reduce energy use, especially with renewable energy sources, using insects as feed is not always advantageous. In other scenarios, their environmental footprint would exceed that of standard compound feed.

Regarding water use, the results are more straightforward. Substituting traditional feed with insects would significantly increase water consumption. The substrate for feeding insects was a major driver of water consumption, especially if insects were fed crop products, which are commonly used as a substrate (Miglietta *et al.*, 2015; van Huis & Oonincx, 2017). Additionally, the use of water for activities like mixing substrates, slaughtering insects, and maintaining facility hygiene can be significant in some cases

(Roffeis *et al.*, 2020; Quang Tran *et al.*, 2022). It is worth adding that only a few studies addressed water consumption, and methodologies for calculating water footprint are still evolving and may not always provide wholly accurate results.

Insects grown on a standard diet require between 0.42–0.82 m³ of water per kilogram of fresh insects (Halloran *et al.*, 2017; Suckling *et al.*, 2020). This figure is around 1.26 m³ per kilogram of dry weight (Bava *et al.*, 2019) and 0.71 m³ per protein unit (Halloran *et al.*, 2017). Insects reared on food waste display a range of water use, around 8.5–11 m³ per kilogram of fresh insects (Roffeis *et al.*, 2017) and 0.8–1.1 m³ per kilogram of dry weight (Bava *et al.*, 2019). The variation is even more pronounced for insects fed manure, ranging from 8.5–11 m³ per kilogram of dry weight (Roffeis *et al.*, 2017) to 113.9–187.6 m³ (Roffeis *et al.*, 2015). There remains a significant research gap regarding the water footprint of insects raised on food scraps and manure.

Overall, Smetana, Bhatia et al. (2023a) considered a potential range of 0.4–0.8 m³ of water per kilogram of insect, aligning with the lower impact estimates. In contrast, producing a kilogram of compound feed incurs a water footprint of just 0.0179 m³. Consequently, insect farming is unlikely to offer environmental benefits regarding water consumption.

However, it is important to consider the potential for improvements in insect farming systems. Many of the studies analysed were conducted in small-scale facilities, and technological advancements in production scalability could reduce environmental impacts (Halloran *et al.*, 2016; Smetana *et al.*, 2019, 2021b; Wade & Hoelle, 2020; Quang Tran *et al.*, 2022). Upscaling insect production could lead to more efficient resource use, and there is room for improvement, especially if insects were to be reared on non-utilised side streams (Smetana *et al.*, 2019; Bosch *et al.*, 2019; Food Standards Agency, 2023).

Switching to renewable energy is also crucial to reduce GHG emissions, although “it is unlikely that on-site renewables will be a solution for all insect producers” (Smetana *et al.*, 2019).

[FIGURE 4 ABOUT HERE]

4.3. Aquaculture feed: Environmental impacts of insects as a feed for aquaculture

Several studies have specifically examined the environmental impact of using insects as feed in aquaculture. Aquaculture as a market is rapidly expanding in response to the increasing world population and demand for seafood, accounting for 46 percent of seafood production in 2018 (FAO, 2020; Quang Tran *et al.*, 2022). This growth poses significant environmental challenges, including the depletion of forage fish stocks, impacts on natural resources, and waste generation (Piedrahita, 2003; Tacon & Forster, 2003; Amirkolaie, 2011). There is increasing evidence that wild fish production is nearing its ecological limits, which could lead to future shortages of fishmeal and fish oil, widely used in aquafeeds (Quang Tran *et al.*, 2022). There is an increased use of by-products from fisheries and aquaculture, but it will not be enough to meet the demand, meaning that replacements will be needed (Froehlich *et al.*, 2018; Jannathulla *et al.*, 2019).

Plant-based feeds like soy meal are increasingly used as fish feed. However, soy is linked with environmental impacts like deforestation, although efforts to source soy more sustainably are underway (Schilling-Vacaflor & Gustafsson, 2024). Moreover, plant-based feeds may not match the nutritional profile of fishmeal, resulting in lower production yields from aquaculture (Silva *et al.*, 2018). Nutritional aspects are important, as insect-derived feed ingredients can enhance the quality of farmed fish, a factor that mass-based comparisons of environmental impacts may overlook (Liverød, 2019).

Quang Tran et al. (2022) conducted the latest systematic review of the environmental effects of aquafeed as a new protein source. They noted a general scarcity of data in this area. The study concentrated on the only insect species for which LCAs have been conducted for feed: BSFL, yellow mealworm, and common housefly. Their findings showed that the environmental impacts of using insects in aquaculture varied, with some categories showing higher impacts, and others lower impacts, compared to conventional protein sources. The discrepancies between various studies (Smárason *et al.*, 2017; e.g. Le Féon *et al.*, 2019; Stejskal *et al.*, 2020) can be attributed to differences in data sources, fish diet formulations, and the proportions in which the diets were modified.

Compared to conventional protein sources, insect meals showed an "immense impact", contributing to a greater carbon footprint than fishmeal and soybean meals (Quang Tran *et al.*, 2022). Compared with soy meal, insect meal exhibits lower land use impacts, suggesting better land use efficiency (van Zanten *et al.*, 2015; Salomone *et al.*, 2017; Thévenot *et al.*, 2018; Smetana *et al.*, 2019). However, it still requires more land than fishmeal. Incorporating insect meal into fish feed reduces the economic fish-in fish-out ratio (eFIFO) compared to fishmeal. This implies a decreased need for marine forage fish to produce the same amount of aquaculture fish, reducing the pressure on marine resources. The water footprint of insect meal production shows contradictory results depending on the study. While the water consumption of the BSFL meal is comparable to that of fishmeal and inferior to plant products (Smetana *et al.*, 2019), some studies for other insects indicated significantly higher water use (Roffeis *et al.*, 2015, 2020). Lastly, adding mealworms and BSFL to fish diet significantly increases faecal nitrogen waste production (Weththasinghe *et al.*, 2021), a key contributor to eutrophication in aquatic ecosystems (Piedrahita, 2003; Amirkolaie, 2011). Higher nitrogen waste production may cause higher ocean acidification (Quang Tran *et al.*, 2022).

As such, with the exception of pressure on forage fish, insect meal tends to have a higher environmental impact across all categories than fishmeal. In the analysis by Quang Tran et al. (2022), the main benefit of using insect meal over traditional fishmeal was the reduced reliance on marine forage fish. However, for that to happen, several factors must be considered.

An important element is the sustainability of future fisheries. Properly managed fisheries work on maintaining stable fish stocks to ensure consistent yields over the long term. Successful examples of quota systems and total allowable catch strategies underscore the importance of effective management (Chu, 2009; Hoshino *et al.*, 2020). Poorly managed fisheries will need to be well-managed in the long-run in every case (Hammer *et al.*, 2010; van Gemert & Andersen, 2018).

Utilising insects involves trade-offs: reducing impact in one area may increase it in another. While insect meals show benefits in terms of forage fish depletion (compared to fishmeal) and land use (compared to soy meal), these insect meals exert an "enormous impact" on global warming potential, energy use, water consumption, acidification by nutrient pollution, and eutrophication (Quang Tran *et al.*, 2022). Consequently, significant improvements are necessary to make insect meal a sustainable feed ingredient.

Additionally, a 2022 LCA focused on salmon farming found that switching from a fish-based diet to an algal–insect diet resulted in a higher impact for most indicators, including climate change, resource use, energy use, terrestrial, marine and freshwater eutrophication, and acidification (Goglio *et al.*, 2022). Biodiversity impacts were not assessed.

In contrast, alternative feed formulations may offer more positive outcomes. For example, a study designed eco-formulated diets for trout, incorporating changes like reducing fishmeal and fish oil by 50%, substituting soy meal with rapeseed meal, and using animal co-products (Wilfart *et al.*, 2023). These eco-diets resulted in lower environmental impacts across all categories compared to conventional diets, including reductions in GHG emissions (-46%), water dependence (-44%), and energy use (-42%). Growth rates were comparable in the short term, although probably lower in the long term. Although the authors considered whether to use insects for the eco-diet, their inclusion was not pursued due to high costs and comparatively higher climate impacts.

The uncertainty surrounding these environmental and ecological impacts leads to a cautious stance towards endorsing insect-based fish feed, especially as commercially viable plant-based alternatives exist. Due to several environmental concerns, the Global Animal Partnership's Atlantic salmon welfare standard, recognised as one of the "most welfare-comprehensive" standards for the aquaculture sector, included a ban on insect-based feed ingredients (Fletcher, 2022).

4.4. Chicken feed: Environmental impacts of insects as a feed for chicken

Several studies have examined the environmental impacts of using insects as feed for chickens in order to reduce reliance on soy, which is associated with sustainability challenges such as deforestation. The inclusion rate of insect meal in chicken feed is limited to 10% (Gasco *et al.*, 2023), leaving the environmental impact of the remaining 90% of the feed unchanged.

In any case, research on the sustainability of using insects as chicken feed in Western contexts is sparse (Smetana *et al.*, 2016, 2019; Ites *et al.*, 2020), and significant uncertainties remain. Vauterin et al. (2021) provide the most complete review on the topic, assessing the potential of insect-fed broiler chickens for meat production. This study focused on global warming potential but not on other environmental indicators. It is important to note that given the significant variability and uncertainty in the studies they reference, their findings are indicative rather than precise comparisons.

According to their findings, broiler chickens fed on insects reared with industrial animal feed, such as grain-based products, tend to have higher greenhouse gas emissions compared to chickens fed with soybeans (averaging 25.82 vs 18.50 kg CO_2eq per kg of protein, respectively). In contrast, when insects are raised on industrial side-streams, GHG emissions from chickens could be lower than from soybean-fed chickens, averaging 17.38 kg CO_2eq per kg of protein. The variation in emission levels is less stark than in other studies, as the results from Vauterin (2021) aggregate data from a diverse range of studies, not limited to optimal scenarios. Moreover, they average the values across various insect species, not solely BSFL, as is often the case. Since some species are less efficient, this influences the overall average.

For both scenarios – insects reared on industrial feeds and by-products – the maximum GHG emissions for insect-fed broilers can be significantly higher than conventional broilers (with maximums of 75.14, 33.97, and 27.60 kg CO_2eq per kg of protein, respectively). The minimum values, however, are relatively similar (around 12.50 kg CO_2eq per kg of protein, with waste-fed insects at 10.65 kg CO_2eq per kg of protein).

To anticipate future improvements and technology potentials, the authors also considered a scenario where they selected only the best practices and lowest GHG values for each insect species. When insects are raised on industrial feeds, insect-fed chickens have comparable, if not slightly higher, GHG emissions than soybean-fed chickens (an average of 18.63 and 18.50 kg CO_2eq per kg of protein, respectively). If insects are fed with waste, there could be a more substantial reduction in GHG emissions (an average of 12.38 kg CO_2eq per kg of protein). However, the applicability of these results in an industrial context remains uncertain due to the lack of large-scale studies on waste as a substrate. Many studies for insects fed with side streams are based on pilot-scale, small-scale, or hypothetical production scenarios (except for *Eisenia fetida*).

Therefore, the carbon footprint of broiler chickens fed with insects may not be more favourable than those fed on a conventional diet, and would likely be higher. This is especially relevant when insects are fed commercially formulated feeds (IPIFF, 2018). The authors conclude that “current practices of insect production for feed purposes are not yet efficient enough to significantly contribute toward a global warming potential reduction in European food consumption" (Vauterin *et al.*, 2021).

Some argue that insect-based feeds would help reduce the environmental impacts caused by soy (Sogari *et al.*, 2022, 2023b), which accounts for two-thirds of the world's global protein feed production because of its exceptional nutritional quality (Cromwell, 1999; Sogari *et al.*, 2022). In Europe, soy is primarily imported from South America (Efeca, 2020) and is often criticised because of sustainability challenges like deforestation and biodiversity loss (Lathuillière *et al.*, 2017; Fehlenberg *et al.*, 2017). The situation in the US is rather different, as the country is the world's largest soy producer, accounting for about 35 percent of global production in 2018 and therefore not needing to rely on imports (Ritchie, 2021). Meanwhile, the environmental impact of soy production in the US is comparatively lower.

In any event, it is not obvious that insects are more sustainable than soy. As seen so far, the comparison between the performance of insect meal and soy meal presents mixed results, whether on GHG emissions (Vauterin *et al.*, 2021) or land use (Smetana *et al.*, 2023a). Furthermore, in Vauterin et al. 2021, the greenhouse gas (GHG) emissions associated with soybean meal were derived from data sourced in South America, encompassing deforestation estimates. Moreover, ongoing initiatives aim to enhance the environmental sustainability of soybean production, such as adopting sourcing practices that exclusively involve soy cultivation on lands not recently subjected to deforestation. The EU has also taken significant steps in this direction, such as the 2023 regulation for deforestation-free supply chains, mandating companies to confirm that products like soy are not linked to deforestation (Regulation (EU) 2023/1115).

In the UK, several initiatives aimed at transitioning to deforestation-free soy emerged, such as the UK Sustainable Soya Initiative, supported by the WWF, and the UK Soy Manifesto (Cullinane, 2019; McCulloch, 2021). The latter is an industry commitment signed by actors representing more than 60% of

UK soy imports to ensure deforestation-free soy shipments by 2025 (UK Soy Manifesto 2023). In 2021, an estimated 64% of the UK's soy consumption was either covered by a certification standard or sourced from areas with lower deforestation risks (Efeca, 2022). The transition towards sustainable soybean production holds the potential to substantially decrease greenhouse gas (GHG) emissions, surpassing by far the potential impact of transitioning to insect-based feeds. Opting for certified soybeans from tropical regions instead of Brazilian soybeans has been posited to potentially result in an approximately 47% reduction in the GHG emissions associated with soybean meal (Hörtenhuber et al., 2014; Vauterin et al., 2021).

4.5. Environmental impacts when insects are fed with waste

The utilisation of food waste as a substrate for insect farming is frequently suggested as a prospective solution to yield environmental advantages and enhance the circularity of the food system. Under one definition, food waste includes agricultural and manufacturing co-products/byproducts, residuals and refusals from food preparation and processing, and household and catering waste (Dou, Toth & Westendorf, 2018).

This section will subsequently delve into an examination of the environmental repercussions associated with insect farming when food waste is employed as a substrate. However, it is noteworthy that a majority of existing insect farms do not currently employ this practice, partially due to regulatory constraints that prohibit the use of certain proposed waste products on the grounds of public health regulations (Salemdeeb *et al.*, 2017; Ffoulkes *et al.*, 2021; Mancini *et al.*, 2022). Also, certain insect species, like crickets and yellow mealworms, have limited potential to be fed on household waste (Le Féon *et al.*, 2019; Harsányi *et al.*, 2020; Quang Tran *et al.*, 2022; Faes, 2022). They perform better on high-quality feed such as crop byproducts, but these can often serve as aquaculture and livestock feed. In contrast, BSFL is more adaptable and capable of consuming a broader array of food waste.

Broadly speaking, feeding insects with wastes, food processing by-products, or manure rather than commercial grain-based coproducts tends to reduce the environmental impact of the resulting insect-derived products (van Zanten *et al.*, 2015; Smetana *et al.*, 2016, 2021b; Salomone *et al.*, 2017; Roffeis *et al.*, 2017; Bosch *et al.*, 2019; Ites *et al.*, 2020). The exact impacts can vary significantly, with GHG emissions ranging from a beneficial –6.42 to 5.3 kg CO_2eq as discussed above (Thévenot *et al.*, 2018; Smetana *et al.*, 2019; Bosch *et al.*, 2019; Ites *et al.*, 2020). The use of manure as feed for insects also shows potential for environmental benefits, although the results are mixed, ranging from 0.77–12 kg CO_2eq for dried insects (Roffeis *et al.*, 2017) to 1–7 kg CO_2eq for protein (Bosch *et al.*, 2019). The scarcity of studies and the lack of industrial-scale research make it challenging to predict how these findings would scale up.

Feeding insects with different waste materials yields different environmental outcomes (Quang Tran *et al.*, 2022). For instance, feeding BSFL with brewery grains has been shown to have a positive environmental impact, as insects avoid costly waste treatment processes, whereas potato peels have a negative one (Ites *et al.*, 2020). Using expired food appeared to make no significant difference. The suboptimal results associated with potato peels and expired food can be attributed to the inefficiency of rearing insects on these substrates, leading to extended growth periods and reduced productivity. In some studies, BSFL fed on cattle manure and municipal waste had better environmental impacts than traditional animal feeds such as beet pulp (Smetana *et al.*, 2016). However, these waste-fed BSFL had similar impacts compared to other animal feeds such as distiller's grains with solubles. They also had lower impacts when fed on maize distiller or spent grain substrates (Bava *et al.*, 2019; Scala *et al.*, 2020). Houseflies were "found to thrive on manure" (van Huis & Oonincx, 2017), with "chicken manure more environmentally efficient than sheep manure" (Roffeis *et al.*, 2020), both as cited in Quang Tran et al. (2022).

Compared to traditional waste treatment methods (landfill, incineration, composting, biogas and bioconversion plants), utilising waste as feed for BSFL has shown encouraging results on several metrics, though anaerobic digestion outperformed BSFL on global warming potential (Mondello *et al.*, 2017; Ites *et al.*, 2020). Food waste as fish and livestock feed usually has lower environmental impacts than anaerobic digestion (Shurson, 2020).

Transportation is another vital factor to consider. When Liverod 2019 included the transportation of feed substrate into their LCA (wheat bran moved over 500 km), the environmental impacts of BSFL rearing increased in most categories, with CO_2 emissions and energy use increasing by 67 percent (Ites *et al.*, 2020). However, these impacts were lower if they used local residues, as observed for mealworms fed with food waste from local bakeries or breweries. The substrate's geographical origin is important for insect production's environmental and socioeconomic performance (Roffeis *et al.*, 2020), and "locally available by-product streams should be preferred" (Derler *et al.*, 2021).

Ultimately, the environmental benefits of using the BSFL as a waste-to-feed solution depend on the specific feed source and its origin. Therefore, the positive outcomes observed with certain feed types cannot be generalised across all waste materials or insect species without thorough evaluation (Ites *et al.*, 2020).

Furthermore, conventional livestock can also consume some waste products.. Agricultural co-products, byproducts, and food-processing residuals are already widely used as animal feed and account for nearly 30 percent of global livestock feed intake (Mottet *et al.*, 2017; Dou *et al.*, 2018; McBride *et al.*, 2021; Food Standards Agency, 2023). Food waste from the hospitality sector and households and surplus products from bakeries and confectioneries could serve as protein sources in livestock diets (Pinotti *et al.*, 2021; Food Standards Agency, 2023). Notably, some substrates mentioned in the previous section as appropriate for insect nutrition are already widely used as livestock feed, such as brewery grains, spent grains, and distiller grains with solubles. Consequently, the range of waste exclusively suitable for insect consumption is narrower than usually assumed. Given this, using waste-fed insects as animal feed would be "inherently less efficient" than feeding food waste to animals directly (Salemdeeb *et al.*, 2017). Certain waste types, like manure, are unsuitable for conventional livestock and can be ingested by some insect species, but also bring drawbacks for production (e.g. higher mortality rates) and obvious health concerns.

Comparative studies on the environmental impacts of waste-fed insects versus waste-fed conventional farm animals are scarce. The only study we found, realised by the WWF, assessed the environmental impacts of three food-waste-to-feed pathways for egg production (McBride *et al.*, 2021). The first scenario converted food waste from retail outlets into feed for BSFL, which was then processed into a meal for hens. The other two scenarios directly fed hens with processed food waste from retail outlets or bakery by-products from food manufacturing plants. The findings did not conclusively identify the most environmentally friendly option among these types of food waste, as the results were mixed across various environmental indicators. BSFL meals had the most significant impact in three categories: global warming potential, water consumption, and marine eutrophication impacts, although they required less land use (Table 3).

Regarding GHG emissions and water consumption, the BSFL diet fares worse than the baseline diet. However, it shows a significant improvement in land use and comparable results for marine eutrophication. GHG emissions are largely driven by the energy consumed during processing. When food-waste-based ingredients were processed using renewable solar energy instead of conventional energy sources, the carbon footprint of these alternative diets was reduced by 0.1 percent (bakery meal at 5 percent) to 51 percent (BSFL at 15 percent). Nonetheless, even with these enhancements, “all BSFL diets and all food waste feed diets still have a higher [GHG emissions] than the baseline diet”.

[TABLE 3 ABOUT HERE]

4.6. Environmental impacts of frass

For the purposes of this paper, "frass" refers a residue left by insect farming, consisting of excrements, leftover substrate, and insect body parts (Commission Regulation (EU) 2021/1925). In the case of BSFL, frass can account for over a third of the original substrate’s weight (Basri *et al.*, 2022). The forecasted growth of insect production will generate high quantities of frass, which will need to be managed in an efficient and sustainable way (Gebremikael *et al.*, 2020; Houben, Daoulas & Dulaurent, 2021; Watson, Houben & Wichern, 2022).

The insect industry has proposed using frass as a fertiliser (Basri *et al.*, 2022). Most of the relevant data comes from the EU. Frass is central to the claims that insects can contribute to a circular economy, allowing the recirculation of nutrients, especially if insects were to consume food waste (Poveda, 2021). Its application could potentially help offset the environmental impacts associated with conventional fertilisers, which include high energy and resource consumption, and pollution leading to eutrophication and soil acidification (Savci, 2012; Schmitt & de Vries, 2020; Chojnacka, Moustakas & Witek-Krowiak, 2020). While there are suggestions of using frass as biochar, animal feed or feedstock, there is less data on these applications (Basri *et al.*, 2022), and using frass as animal feed is still prohibited in the UK, the US and the EU.

Some studies point out frass's potential to benefit soil microbial biomass (Gebremikael *et al.*, 2020), supply macronutrients to plants (Houben *et al.*, 2020), work as a soil amendment and stimulate plant growth (Schmitt & de Vries, 2020; Poveda, 2021; Watson *et al.*, 2022; Gasco *et al.*, 2023). Its composition resembles chicken manure.

However, some studies note negative effects on soil processes, such as excessive nitrite accumulation in the soil (Watson, Preißing & Wichern, 2021) or inhibited seed germination (Kawasaki *et al.*, 2020). Additionally, the impacts of frass "vary significantly depending on the substrate used to grow larvae" (Gebremikael *et al.*, 2020). While several studies indicate that frass can increase yield, others reported negative growth, probably associated with the phytotoxicity of the frass (Kagata & Ohgushi, 2012; Alattar, Alattar & Popa, 2016; Berggren *et al.*, 2019; Lopes, Yong & Lalander, 2022).

Some studies suggest that replacing chemical fertilisers with frass reduces environmental impacts in some categories (Smetana *et al.*, 2019; Schmitt & de Vries, 2020). These studies observed a reduction in both aquatic and terrestrial acidification (with decreases of 0.064g and 0.265g of SO_2 equivalents per kilogram of frass used, respectively). Aquatic acidification is the process where water bodies become more acidic, often due to SO2 emissions, and terrestrial acidification is a similar process affecting soil. However, aquatic eutrophication remained at levels similar to those associated with traditional fertilisers (eutrophication happens where an excessive amount of nutrients in water bodies leads to intense plant growth and subsequent depletion of oxygen). Phosphate in frass can present a potential risk to water sources (Ffoulkes *et al.*, 2021). Moreover, the dynamics of how frass affects nutrient supply in soil are poorly understood, necessitating further research (Gebremikael *et al.*, 2020; Houben *et al.*, 2021; Lopes *et al.*, 2022). Most existing studies are small-scale, with limited insights into long-term impacts.

A key concern is that frass's stimulatory effects on the soil may have negative environmental impacts, which have been largely overlooked until now. Several studies have reported significant greenhouse gas emissions from soils amended with frass (Gebremikael *et al.*, 2020; Houben *et al.*, 2021; Rummel *et al.*, 2021; Watson *et al.*, 2022). One study demonstrated that due to an increase in basal respiration, soils treated with frass emitted considerably more CO_2 than those treated with conventional compost or left unfertilised (Fuhrmann *et al.*, 2022). Another study found that frass altered soil microbial composition, changing nutrient fluxes and leading to substantial carbon and nitrogen releases (as CO2, CH4 and N2O) (Rummel *et al.*, 2021). According to the authors, "very high" GHG emissions were reported, "undermining the potential environmental benefit of insect-based protein production and calling for more detailed analyses before frass is widely applied in agriculture" (Rummel *et al.*, 2021).

Contamination is another serious issue. When insects are fed with waste, there's a risk that frass could contain pathogenic microorganisms (Basri *et al.*, 2022). Research has identified potential foodborne pathogens in frass, including *Salmonella spp*., *Xanthomonadaceae*, and *Bacillus cereus*, likely originating from the substrate (Wynants *et al.*, 2019; Kawasaki *et al.*, 2020). High-temperature treatments, while potentially eliminating harmful microbes, could also destroy beneficial microorganisms and biomolecules that enrich soils (Poveda, 2021). Attempts to sanitise the substrate by sterilisation have been shown to reduce the efficiency of BSFL rearing and may negate the benefits of frass as a fertiliser (Gold *et al.*, 2020a).

An open question is whether frass will be economically competitive with more traditional fertilisers, which is necessary if frass is going to be used as fertiliser in large volumes. In the EU, frass received authorisation as a fertiliser in November 2021 (Commission regulation 2021/1925). Despite this, the frass market faces significant competition from organic fertilisers, particularly livestock manure, which already saturates the EU fertiliser market (Ffoulkes *et al.*, 2021). More manure is generated than is used as a fertiliser (Cox, 2019). As a result, some insect producers have resorted to exporting their frass abroad as a means of disposal (Ffoulkes *et al.*, 2021).

Frass as a fertiliser has not taken off to date. Market growth is further hindered by regulatory constraints, such as the requirements for heat treatment and limits on the inclusion of insect body parts and eggs in frass (Eurogroup for animals, 2023). The insect industry is currently lobbying to reduce or remove some requirements, such as heat treatment. This would indicate that frass as a fertiliser is not economically viable under current health regulations. Moreover, the removal of heat treatment would raise concerns about the ecological and health implications of spreading untreated insect waste in the environment (Poveda, 2021; Basri *et al.*, 2022).

The market for organic fertilisers, smaller than that for chemical fertilisers, poses additional challenges. Organic fertilisers, including frass, offer environmental advantages but often require more labour and financial investment (Wang *et al.*, 2018). They also tend to be costlier to transport over long distances. These factors raise doubts about the capacity of insect frass to substantially reduce the usage of chemical fertilisers.

If waste is not revalorised in another way, insect waste will need to be disposed of. In that case, the massive amount of frass from insects can become a serious environmental problem (Poveda, 2021). Only a limited amount of material can be stored onsite as frass can become hazardous if not disposed of or utilised promptly (Ffoulkes *et al.*, 2021). Reports indicate that already existing struggles with maintaining large volumes of conventional livestock manure lead some farmers to resort to illegal disposal methods (Wasley *et al.*, 2017; Cox, 2019). This practice is considered an “environmental crime” and represents a large threat to ecosystems and biodiversity due to eutrophication (Neve, 2023, p. 52). Managing insect farm waste could replicate the environmental issues associated with traditional aquaculture and livestock production, particularly regarding air and water pollution (European Food Safety Authority, 2015; Halloran *et al.*, 2016).

Before stressing the potential of frass in contributing to a circular economy, more data is needed to understand its wider impact (Watson *et al.*, 2022). Notably, limited research exists on frass’s impact on soil carbon and nitrogen release. Studies like those of Rummel et al. have shown that these releases can substantially increase the environmental footprint of insect-based products and diminish the value of frass as a fertiliser and organic amendment. These findings should be integrated into future life cycle assessments, and further research is needed before frass is applied widely in agriculture (Watson *et al.*, 2022).

5. Economic viability

One other aspect of a sustainable food system is economic viability. Economic competitiveness is crucial, as many products and technologies considered more sustainable have failed to displace conventional ones because of their higher costs, such as green plastics, eco-friendly insulation materials, or organic meat.

Consider the case of fishmeal, which is a major market targeted by insect producers. Unless insect meal becomes a more cost-competitive option, it is unlikely to reduce the pressure on marine forage fish considerably. Insect meal will need to be more cost-competitive than fishmeal to replace it. Fishmeal prices are around 1,800 USD per ton in 2023 (IndexMundi, 2023; World Bank 2023), with the OECD and FAO predicting a decrease to around 1,250 USD per ton in 2031 (OECD/FAO, 2022). Insect meals, however, tend to be more expensive, and this price disparity might persist in the future. Rabobank (2021) estimates insect meals' current price to be in the range of 3,800 to 6,000 USD per metric ton. Even when the sector is scaled up and reaches maturity, projections beyond 2030 still expect prices in the range of 1,600 to 2,700 USD. Aso, insect meal (defatted and full fat) has lower protein content than fishmeal (Janssen *et al.*, 2017b; Gold *et al.*, 2020b; Chia *et al.*, 2020; Smets, Claes & Van Der Borght, 2021; Fitriana *et al.*, 2022). This suggests that insect meal would be less valuable than fishmeal of the same weight.

Moreover, the market might adapt to using fishmeal in sectors where insects are not competitive. In a hypothetical scenario where insect meal becomes cheaper than fishmeal, it could affect other industries relying on fishmeal. As of 2020, approximately 15 percent of fishmeal was used in pig feed and 20 percent in shrimp feed (IFFO 2022). However, the insect feed market is not anticipated to have a significant share in pig feed and is still emerging for shrimp feed, with limited inclusion rates (IPIFF, 2021; Gasco *et al.*, 2023). If insect meal becomes more cost-effective than fishmeal, it could reduce fishmeal demand, potentially lowering its price. This price drop might make fishmeal more attractive to other sectors like pig or shrimp feed, boosting demand from these sectors. The fishmeal sector has consistently adapted to changing demands in the past, shifting from poultry and pigs to salmonids and shrimps, with uncertain future trends (IFFO 2022).

6. Conclusion

In this report, we have critically examined the scientific literature relating to the environmental impacts of insect farming. Our key conclusions are as follows:

1. Insects' environmental viability is highly dependent on their diet, the source of feed, and the specific end-use product that insects are being used to replace.
2. The ideas that insects can be fed on food waste and that insect frass can be used as fertiliser have significant challenges to overcome at commercial scales.
3. Replacing aquaculture and livestock feed with insect-based products could be environmentally beneficial only in the cases of extremely efficient production systems. These systems might include insects raised on waste or low-cost feeds and utilising side-stream heat and renewable energy sources (e.g., insects grown on waste or low-cost feeds, relying on side-stream heat and alternative energy sources) (Smetana *et al.*, 2023a). Although such systems could have significantly lower environmental impacts, achieving this requires overcoming numerous economic and technical challenges.
4. While using insect meal instead of fishmeal might mitigate overfishing risks, other environmental aspects such as energy demand, global warming potential, land use and water use favour fishmeal. Compared to soybean meal, the benefits of insect meal lie primarily in reduced land use, depending on the substrate. However, soybean meal is more beneficial in terms of carbon footprint, energy use, acidification by nutrient pollution, and eutrophication (Quang Tran *et al.*, 2022).

5. In contrast to insects as aquaculture and livestock feed, direct human consumption of insects as food could offer environmental benefits. However, the resulting animal products would still have a significantly higher environmental footprint than most categories of foods that insects replace in practice, such as ready-to-eat snacks and cookies.
6. Significant gaps remain in our knowledge, and there has been little research on industrial-scale insect farming in real-world conditions.

Despite a narrative of environmental sustainability, insects as a protein source are not inherently more sustainable than other protein sources. Furthermore, there are large knowledge gaps in the literature, and future research that aims to fill these gaps—that is, comprehensive evaluations of insects farmed in industrial-scale conditions for realistic end-use products—would provide a much stronger foundation for this ongoing policy debate.

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Conceptualization: CB, TBC, DC, MSJ; Investigation: CB, TBC; Writing - Original Draft: CB; Writing - Review & Editing: CB, TBC, DC, KL, RR, MSJ; Visualization: DC, RR; Supervision: DC

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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Tables

Table 1. Examples of feed conversion rates (FCR) in insects and conventional livestock. Data reproduced from the review by (Jansson *et al.*, 2019) (2019).

	FCR (kg feed/kg growth)	**Reference**
Cricket	1.5–3.9	(Lundy & Parrella, 2015; Miech *et al.*, 2017)
Chicken	1.8	(Sheppard *et al.*, 2009; Patricio *et al.*, 2012)
Mealworm	2.0	(Thévenot *et al.*, 2018)
Pigs (conventional crossbred)	2.6	(Smit *et al.*, 2014)
Beef	> 4.5	(NRC, 2000)

Table 2. Comparison of two life cycle analyses performed on crickets and their relevance for determining the environmental impact of crickets in industrialised production in Western countries.

Study	**Halloran et al.** (2017)	**Suckling et al.** (2020)
Location	Thailand	United Kingdom
Insect species	*A. domesticus; G. bimaculatus*	*G. bimaculatus*
Market	Human consumption	Live pet food
Greenhouse gas emissions	4.2 kg CO_2-eq per kg of protein	33.49 kg CO_2-eq per kg of protein
Strength of study	● Crickets reared for human consumption ● Represents the most reared cricket species (*A. domesticus*)	● Representative of business conditions in the UK ● Heating requirements more representative of Europe ● More recent
Limits of study	● High temperatures with no energy required for heating ● Medium-scale farm ● Farms in Thailand have very diverse farming systems (more than 20,000 farms), and the one studied may not be representative ● Does not represent business conditions in Europe (outdoor setting, factories are less automated partly because labour is cheaper)	● Small-scale farm ● Crickets are not reared for human consumption, which impacts processing methods ● Several inefficiencies due to the need to sell crickets alive, which complicates storing ● Inclusion of the carbon emissions from frass, with several uncertainties

Table 3. Comparison of environmental impacts of three food-waste-to-feed pathways for egg production, in which hens are fed either BSFL meal, food waste feed, or bakery meal at an inclusion level of either 5, 10, or 15 percent. Results are expressed relative to the baseline (100%). Data from McBride et al. (2021).

Diet	**Inclusion level of food waste ingredient**	**Global warming potential**	**Land use**	**Water consumption**	**Marine eutrophication**
Baseline	*100%*	*100%*	*100%*	*100%*	*100%*
BSFL Meal	5%	179%	86%	108%	98%
	10%	265%	73%	123%	100%
	15%	350%	66%	138%	102%
Food Waste Feed	5%	116%	90%	102%	94%
	10%	131%	79%	104%	88%
	15%	151%	68%	112%	85%
Bakery Meal	5%	97%	96%	97%	96%
	10%	95%	92%	96%	93%
	15%	99%	92%	97%	90%

Figures

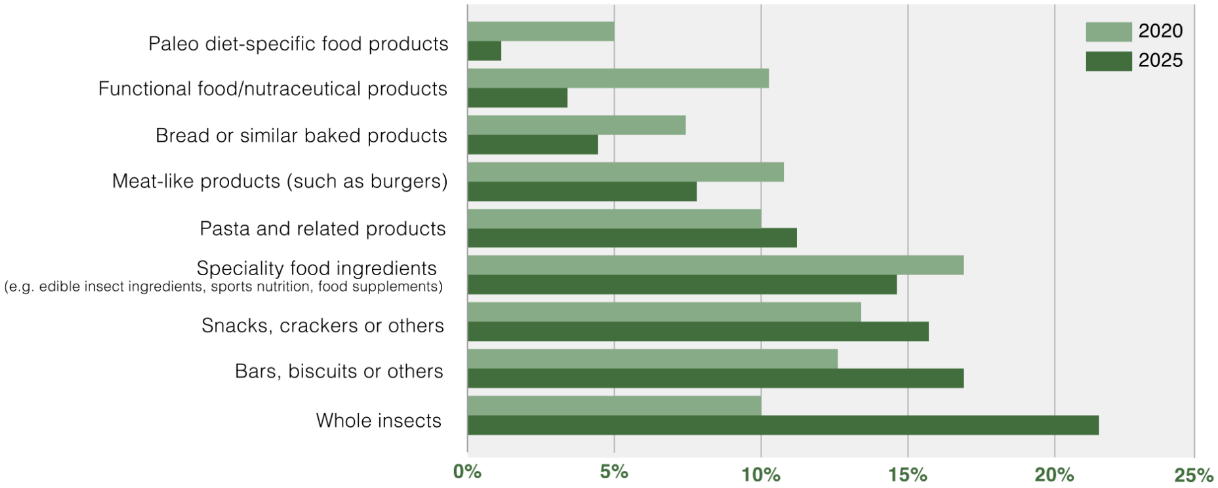

Figure 1. Market share of different insect as food product types, estimated in 2020 (light bars) and projected for 2025 (dark bars). Data: IPIFF (2020a)

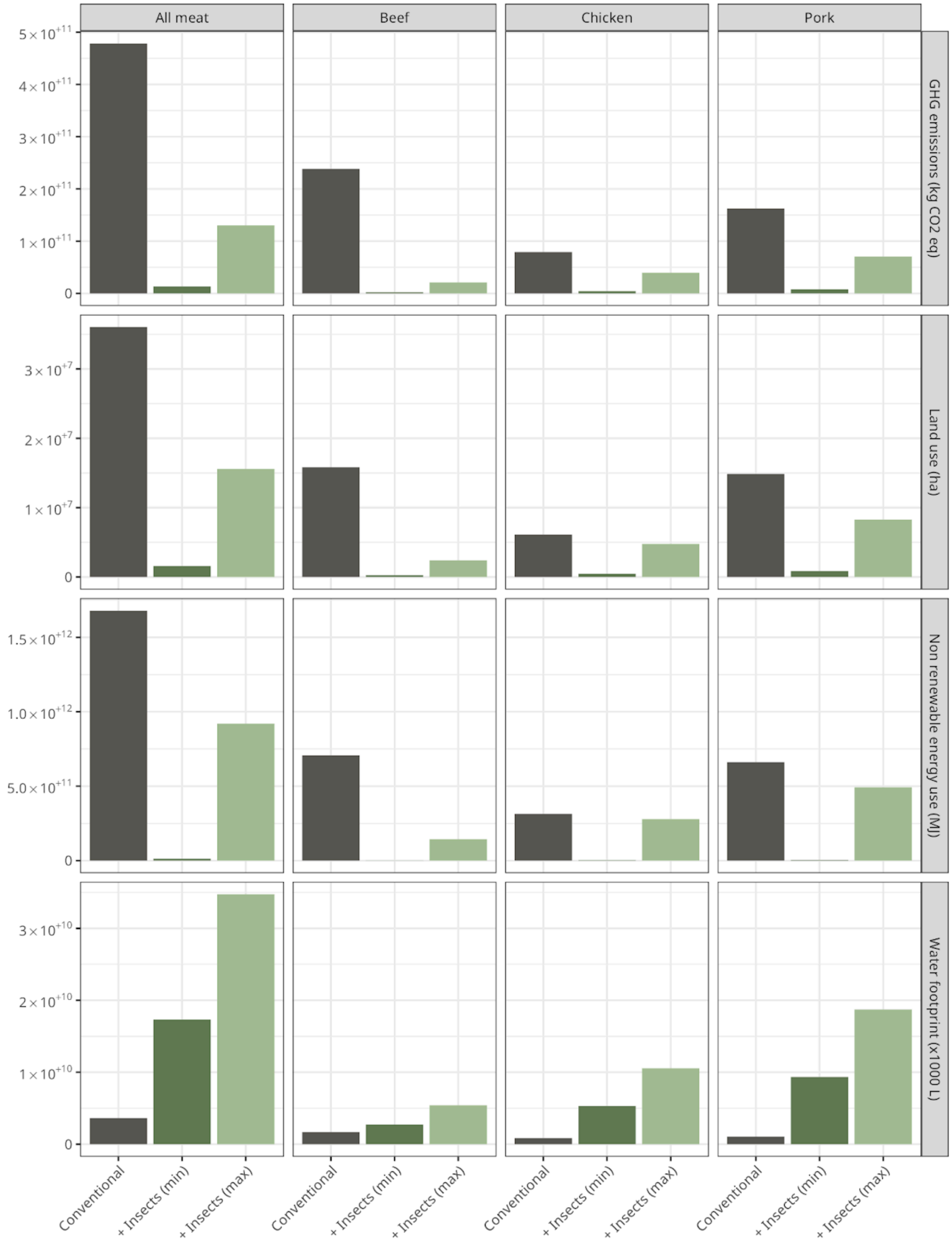

Figure 2. Environmental impacts associated with meat produced in Europe (grey bars) and their changes due to potential substitution with insect biomass (dark green bars for low-impact scenario; light green bars for high-impact scenario). Data from Smetana et al. (2023a).

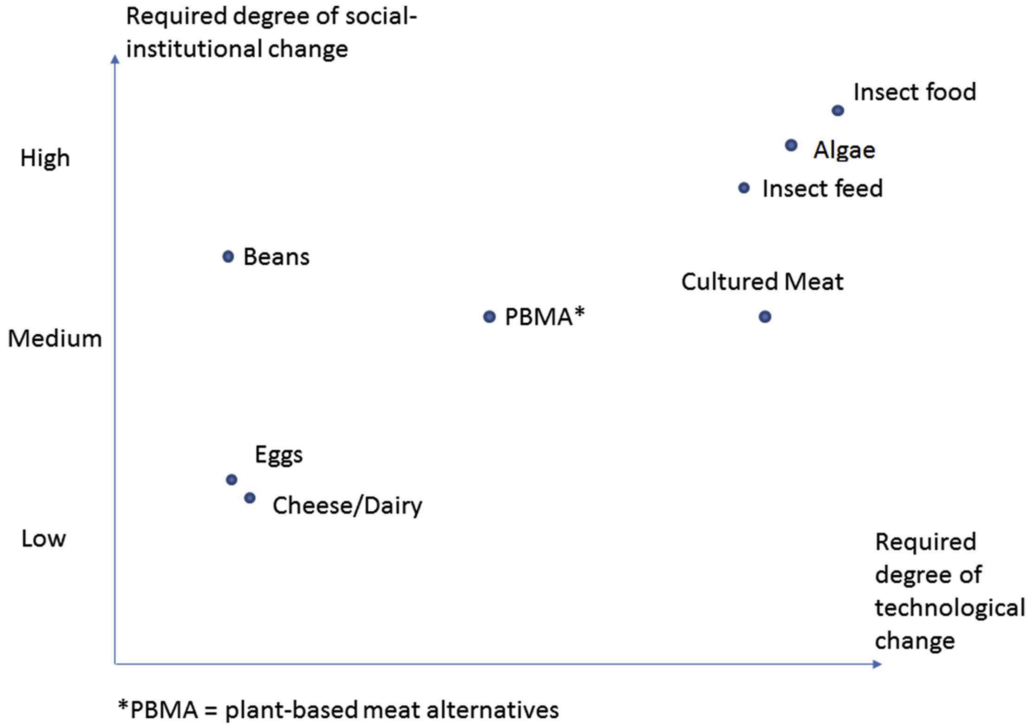

Figure 3. Degree of social-institutional and technological change required for meat alternatives. Graph reproduced from van der Weele et al. (2019) under CC-BY licence.

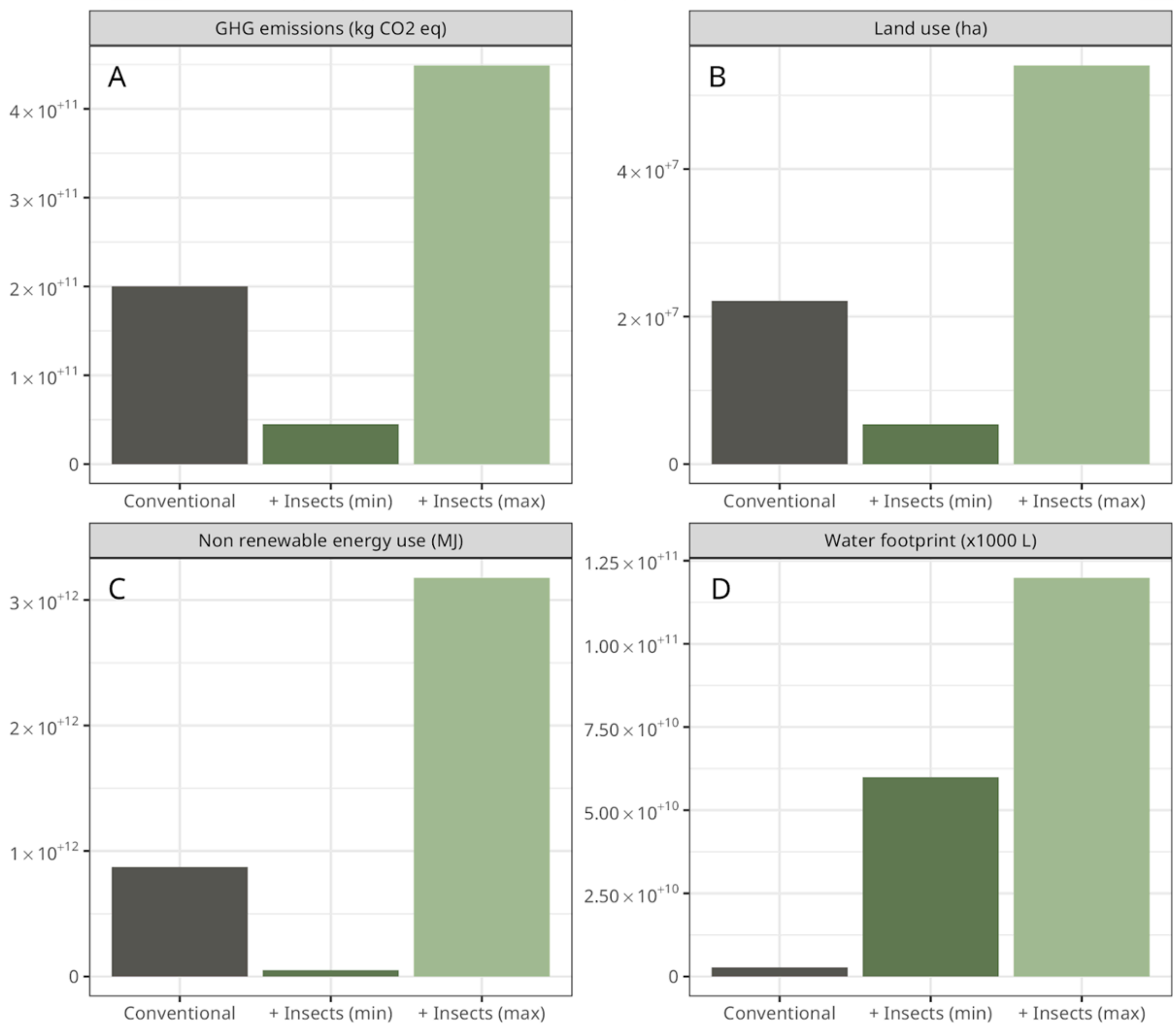

Figure 4. Environmental impacts associated with livestock feed produced in Europe (grey bars) and their changes due to potential substitution with insect biomass (dark green bars for low-impact scenario; light green bars for high-impact scenario). Data from Smetana et al. (2023a).