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

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Abstract

Though insect farming is widely cited as a potential contributor to a sustainable food transition, many of the benefits commonly mentioned by companies and proponents of insect farming are challenged by current 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 most studies available suggest that when insects are not fed unused food waste, their use in animal feed and pet food results in 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.

Key policy highlights

- This paper provides a comprehensive review of the evidence underlying claims about the environmental impacts of insect farming.
- Significant gaps remain in our knowledge, and there has been little research on industrial-scale insect farming in real-world conditions.
- 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.

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; Xu *et al.*, 2021). Despite consuming 77% of global agricultural land, livestock and feed crops contribute merely 18% of human caloric intake and 37% of dietary protein worldwide. Insect-based products are frequently cited as a sustainable alternative to meat, feed, or pet food. 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).

In recent years, insect farming has witnessed substantial growth, attracting heightened interest from industrial, governmental, and academic sectors (Sogari *et al.*, 2022). Over $1.5 billion has been invested in the insect farming industry (Watson, 2024), leading to the construction of large-scale automated facilities capable of producing trillions of insects, with more such facilities in development. Legislative changes in regions like the European Union have created a more favourable environment for expanding the use of insects as human food, pet 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).

Pet food currently leads the insect-based product market, having captured approximately 50% of market share in 2020 (de Jong & Nikolik, 2021). While earlier forecasts suggested aquaculture feed would become the dominant sector by 2030, recent industry movements challenge this outlook. Notably, market leader Ÿnsect has started pivoting away from the feed sector, redirecting its focus to the more profitable pet food segment (Reus, 2023). Insect-based food products intended for human consumption only account for a very small proportion of investment: less than 5% in 2022 (Eurogroup for animals, 2023).

Insect-based pet food primarily aims to replace conventional cat and dog food, generally focusing on the supposed benefits to the animal's health, insects' allergen-free nature, or insects' environmental advantage. Insect meal targets the replacement of conventional animal feed, especially in aquaculture, and to a lesser extent in poultry. It is mostly promoted as a substitute for fishmeal, which is associated with forage fish depletion, and soy meal, linked to deforestation (Oliva-Teles, Enes & Peres, 2015). Although insect-based foods are often presented as replacements for animal-based products, 90% of them are not meat substitutes (IPIFF, 2020a). In addition, a core value of insect farming lies in its role as a potential waste management activity, and the fact that 'waste' from the insect processing stream can be used in non-food products (Ojha, Bußler & Schlüter, 2020). In particular, insect frass could be used to replace conventional fertilisers, which are associated with significant environmental impacts.

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. This report aims to provide an overview of the environmental impacts of the current large-scale insect farming industry. Therefore, we focus primarily on data from Western countries, especially the EU and to a lesser extent the UK, where most large-scale companies are located. While insect farming is present in other parts of the world, it is typically done on a smaller scale, with very different production contexts, although there is potential for large-scale companies to expand into these regions in the future (Baiano, 2020).

Several arguments seem to support the sustainability of insect farming. Insects are believed to convert feed into protein more efficiently than conventional livestock, with a lower feed conversion ratio (van Huis & FAO, 2013; Halloran *et al.*, 2016). Unlike mammals and birds, insects are exothermic, meaning they do not expend energy to regulate body temperature. Moreover, insects can potentially consume a variety of feed sources, including organic waste (Halloran *et al.*, 2016). However, these characteristics do not inherently ensure the environmental friendliness of insect-based products (Liverød, 2019; Lange & Nakamura, 2023).

Notably, recent research indicates that the industry makes very little use of food waste to feed insects due to several barriers, including nutritional and logistical challenges (Biteau *et al.*, 2024b). Instead, it relies primarily on more expensive, higher-quality ingredients such as commercial feed or agricultural co-products that are suitable for direct consumption by other animals or, in some cases, humans. In this case, 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. Therefore, this study focuses on ingredients that are currently representative of industry practices, while potential future improvements, such as using waste, are discussed separately.

Despite the potential of insect agriculture, significant gaps remain in the literature. Several studies highlight substantial uncertainties, noting that the future environmental impact of large-scale insect production is "largely unknown" (Berggren, Jansson & Low, 2019; Lange & Nakamura, 2023). Although the European Commission has recently approved new uses for insect products, its experts acknowledge an "overwhelming lack of knowledge concerning almost every aspect of production" (EU Platform on Sustainable Finance, 2021).

This review examines the key drivers of the environmental impact of insect farming, followed by a critical evaluation of the empirical evidence regarding its environmental benefits. The first section identifies key factors and knowledge gaps in insect farming. Subsequent sections explore the environmental impacts of insect-based products used as human food, livestock and aquaculture feed, pet food, and fertiliser, in that order. We also address potential biodiversity risks and pathogen concerns. Following this, we discuss potential ways of improving the sustainability of insect farming, focusing on waste utilisation and technological advancements, before briefly examining the economic outlook. The methods section is provided at the end. Through a comprehensive review of current scientific literature, this study aims to identify critical knowledge gaps for future research and provide policymakers with a nuanced understanding of outstanding questions in the field.

2. General considerations regarding the environmental impact of insect farming

The primary determinants of environmental impact in insect farming come from the production of the substrate (the feed given to insects) and the energy required for rearing and processing insects (Smetana, Schmitt & Mathys, 2019; Vauterin *et al.*, 2021).

2.1. Substrate

The feed provided to insects stands out as the most significant contributor to the environmental impact of insect-based products (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 substrates like grains (Halloran *et al.*, 2016; Smetana *et al.*, 2023a; Paris *et al.*, 2024). However, this is not always the case (Shockley & Dossey, 2014; Beyers *et al.*, 2023).

Several factors must be weighed, including the substrate's nutritional content, cost, environmental footprint, the resulting growth rate of the insects, and whether the substrate constitutes an unused side stream (Sogari *et al.*, 2023b). Generally, high-quality substrates such as grains lead to faster growth cycles in insects, but their production often entails a higher environmental impact and may compete with their use as human food or animal feed (Smetana *et al.*, 2016; Spykman *et al.*, 2021). On the other hand, lower-quality substrates 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; Spykman *et al.*, 2021; Beyers *et al.*, 2023). For example, the yellow mealworm's growth cycle spans 26 days on high-quality substrate compared to 103 days on dry, expired food (Ites *et al.*, 2020). Due to these extended rearing times, Ites et al. (2020) failed to identify economically viable ways to rear mealworms on low-value waste. The variability of organic waste complicates finding an optimal feed composition, and longer growth cycles can challenge the economic feasibility (Shurson, 2020; Van Peer *et al.*, 2021). There is generally a trade-off between economic and environmental performance. The environmental impacts of using waste, with the potential benefits of waste removal, are discussed in section 8.1.

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 also demonstrates limited suitability for rearing on organic waste and manure substrates (Le Féon *et al.*, 2019; Harsányi *et al.*, 2020). Regulatory constraints in the European Union, the United States and the United Kingdom limit the use of most waste products as substrates 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' diet, waste-fed insects may be unable to deliver the stable, consistent nutritional content required by aquaculture and livestock industries (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 (IPIFF, 2018; Gibson, 2022; Faes, 2022; Biteau *et al.*, 2024b). These substrates are already widely used as animal feed (Heidari *et al.*, 2021), meaning that insect agriculture usually competes with these established sectors.

2.2. Energy use

Studies show mixed findings on energy use in insect farming, with significant variation based on factors such as building design, location, substrate type, and processing technology. For instance, the impact of energy use on GHG emissions is higher in carbon-intensive electricity grids (Kleyn, 2023). Some studies indicate that heating is the primary driver of energy consumption (van Zanten *et al.*, 2015; Salomone *et al.*, 2017; Smetana *et al.*, 2019), while others suggest that processing accounts for over half of energy use (Thévenot *et al.*, 2018). Other studies find no single dominant factor (Kleyn, 2023). Conversely, a recent study argues that processing the substrate serving as insect feed accounts for the highest non-renewable energy use and freshwater withdrawal, and this contributes to only 1%–5% of the total environmental impact (Smetana, Ristic & Heinz, 2023b).

Regarding heating, insects, being cold-blooded, require external heat to regulate their temperature, with optimal rearing conditions typically between 25–30°C and 50–70% humidity, varying by species (Odhiambo, Ochia & Okuto, 2022; Rho & Lee, 2023; Korir *et al.*, 2024). Growth rates are temperature-dependent; for example, crickets grow in eight weeks at 30°C but take eight months at 18°C

(Ayieko *et al.*, 2015). Longer growth periods increase energy, feed, and water consumption, raising environmental impacts (Halloran *et al.*, 2016).

The geographical location of the factory significantly affects the energy needed for temperature control (Halloran *et al.*, 2016; Maiolo *et al.*, 2021). 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 help mitigate this impact (Quang Tran, Van Doan & Stejskal, 2022). In some production systems, heating accounted for 19% of GHG emissions in the UK (Suckling *et al.*, 2020) and up to 65% of energy use in Austria (Dreyer *et al.*, 2021). Given that temperature and energy mix vary by location, the findings of a study conducted in one context may not directly apply to another.

Insect drying is often highlighted for its energy consumption (Salomone *et al.*, 2017; Roffeis *et al.*, 2017, 2020; Mertenat, Diener & Zurbrügg, 2019; Bava *et al.*, 2019; Ites *et al.*, 2020). It can have a “relatively high energy demand and could result in high associated environmental impacts” (Smetana *et al.*, 2021b). Processing, including drying, can represent 7-45% of electricity used (Bava *et al.*, 2019), more than half of energy consumption (Thévenot *et al.*, 2018) and up to 20% of the overall environmental impact (Goyal *et al.*, 2021).

Some other energy use factors have a smaller influence on the environmental impact of insect production. The impact of transportation 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

(Spykman *et al.*, 2021), but is presumed to be marginal, although this conclusion is based on older studies that may not be representative of emerging fully automated industrial processes (Halloran *et al.*, 2016).

2.3. Major knowledge gaps

When evaluating the environmental impact of insect farming, it is essential to acknowledge the limitations and gaps in existing literature. The following limits apply to all of the insects as food and feed markets, not just pet food.

Consider crickets, one of the species most commonly reared in insect farms. For these species, we found almost no reliable impacts and no estimate for pet food products produced in Europe or other industrialised, Western countries. The few existing studies are difficult to compare because of widely differing parameters considered (See Table 1 for a summary of the differences in parameters between Halloran et al. (2017) and Suckling et al. (2020)). LCA by Halloran et al. (2017) indicated lower GHG emissions for crickets compared to meat, and this finding has been extensively cited. However the data used in Halloran et al. (2017) came from 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 necessary. Suckling et al. (2020), the first commercial-scale insect LCA in the UK, revealed considerably higher GHG emissions, primarily due to heating. Their findings showed emissions nearly ten times higher than Halloran et al. (2017).

Table 1. Comparison of two life cycle assessments 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	● 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 ● Several inefficiencies due to the need to sell crickets alive, which complicates storing ● Inclusion of the carbon emissions from frass, with several uncertainties

This example 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; Smetana *et al.*, 2021a). As of 2021, only four insect-related LCAs had been conducted on actual farms in Europe, including Suckling et al. 2020, with an additional two on pilot farms (Vauterin *et al.*, 2021). Most LCAs have focused on cradle-to-gate analyses, often excluding factors like distribution and transportation (van Huis *et al.*, 2021).

Current 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 widely cited, but may be outdated given the latest developments in this rapidly evolving field and assumptions out of line with current business practices. The most quoted LCA in the field, Oonincx and de Boer (2012), cited in the influential 2013 FAO report, was based on a production system that is not representative of actual large-scale operations, as they considered insects fed with fresh carrots and mixed grains to produce live or frozen insects for birds or reptiles. Moreover, 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; Van Peer *et al.*, 2022). Shine (2020) emphasises that, due to the complexity and diversity of factors involved, LCAs should be conducted for each product under locally relevant conditions. Without such tailored assessments, current numbers should be viewed “more as enthusiastic speculation than actual demonstrable figures” (Shine, 2020)**.**

Several companies, such as Protix and Ÿnsect, present case studies on their production methods, often highlighting highly favourable environmental outcomes. However, these studies are not subject to critical peer review, and the lack of access to source data, along with figures that significantly diverge from the scientific literature (e.g., Protix's claim that its PureeX insect meat uses 99.8% less water than poultry meat), raises concerns about their reliability. In the course of this review, we contacted 5 major insect farming companies (Ynsect, Protix, Innovafeed, Enorm Biofactory and Agronutris), but they did not respond, except Protix that declined to share their environmental data with us for reasons of confidentiality.

3. Environmental impact of insect-based foods

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. Therefore, assessing the ecological impact of insects as food requires understanding what products insect foods are being substituted for. Most scientific research on this topic compares insects to conventional meat (Bordiean *et al.*, 2020; Capestany, 2021; Smith *et al.*, 2021; Abdullahi, Igwe & Dandago, 2022; Vinci *et al.*, 2022; Vale-Hagan *et al.*, 2023) and, to a lesser extent, meat alternatives (Hadi & Brightwell, 2021). Positive environmental results of insect-based foods compared to meat are regularly touted by insect farming companies. While insects aim to offer an additional source of protein, their adoption may not always result in reduced meat consumption (Halloran *et al.*, 2016; Shine, 2020; Cottrell *et al.*, 2021). 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, with almost 90% of insect-based food items being products such as pasta, protein bars, whole insects, or biscuits. This presents an important consideration: if insects do not replace meat, what is their actual contribution to more sustainable food systems?

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).

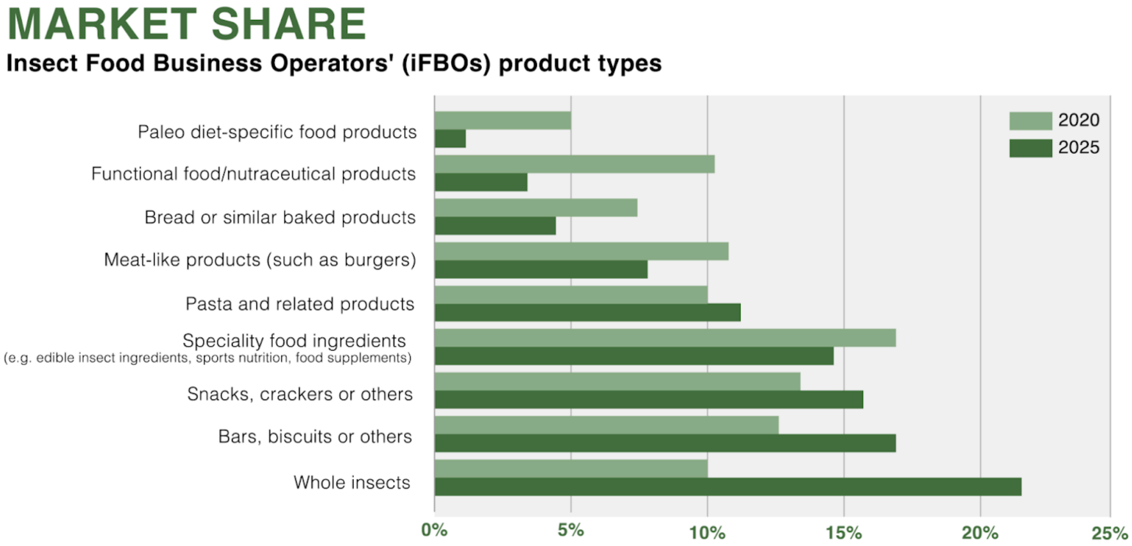

Figure 1. Market share of different insect-as-food product types, estimated in 2020 (light bars) and projected for 2025 (dark bars). Data: IPIFF (2020a)

Except for burger patties or sausages, insect-based foods do not fill the culinary role of meat as it is commonly consumed. Meat-like products only accounted for 8% of the insect food market in 2020, a figure expected to rise but remain below 12% 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), therefore incorporating insects could increase rather than decrease the environmental impact of such foods (Shine, 2020). Even when insect-based products substitute for animal-sourced foods, they may still face competition from more sustainable plant proteins (Lucas, Guo & Guillén-Gosálbez, 2023). For example, while insect protein powder could replace whey protein powder, plant-based protein supplements might offer a more environmentally friendly alternative. In fact, plant-based options accounted for nearly 40% of the protein supplement market in 2023, with projections indicating further growth (Grand View Research, 2023).

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 (Shine, 2020). Insects would primarily compete with plant products. Therefore, comparing the sustainability of insects with meat, as is commonly done in the literature (Baiano, 2020; Kemsawasd *et al.*, 2022; Illa & Yuguero, 2022; Ros-Baró *et al.*, 2022), does not provide a complete perspective. Similarly, most companies selling insect snack bars promote them as environmentally friendly by comparing them to animal products (Andreani, Sogari & Banović, 2024), though there is no evidence showing they are more sustainable than traditional snack bars (e.g. muesli bars). 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. A solution to avoid misleading ideas about insect-based products not replacing meat products could be a standardised carbon label on the packaging of food products, which could help consumers pick the foods with the lowest environmental footprint (Taufique *et al.*, 2022).

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 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).

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). Companies then tend to focus on products that are most appealing to consumers, however, this inherently limits the range of meals that insect-based products can replace.

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.

It should also be noted that a willingness to pay is not a willingness to substitute, especially if insect-based products remain relatively expensive. The success of insects as a meat replacement implies the disadoption of meat, an unspoken assumption poorly addressed in the literature (Cottrell *et al.*, 2021). In an experiment led by Michel et al. (2023) in the UK, 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.

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, especially as they have limited similarities with meat from a sensory, functional, usability and symbolic points of view (Shine, 2020). Replicating the taste, smell, and flavour of animal-based products remains a significant challenge (Malila *et al.*, 2024). Insects are also not expected to reach price parity with meat before plant-based proteins, microbe-derived protein and cultured meat do (Malila *et al.*, 2024). 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. Note that recent efforts have been made to provide new recipes, with some restaurants trying to improve cultural acceptance.

3.3. Environmental impact of insects compared to meat products

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 (Smetana *et al.*, 2023a; Hunter, 2024). Table 3 in section 4.1 provides more data about these impacts.

Insect farming generally yields lower GHG emissions than traditional livestock production. For instance, emissions for insect-based feed range between 2.8 and 11 kg CO2e per kg of dry insect matter (table 3), whereas livestock emissions are substantially higher, with beef emitting approximately 35.0 kg CO2e per kg, pork 6.95 kg CO2e, and poultry 5.97 kg CO2e (Smetana *et al.*, 2023a).

Land use also favours insect farming, with requirements of around 0.16 to 8.0 m^2 per kg of insect product (table 3), much less than the land needed for beef (23.1 m^2/kg), pork (6.28 m^2/kg), and poultry (4.64 m^2/kg). Energy use shows favourable results as well, as insect farming consumes between 0.36 to 21.2 MJ per kg, depending on production methods, which is lower than beef (104.0 MJ/kg), pork (28.3 MJ/kg) and poultry (23.8 MJ/kg) (Smetana *et al.*, 2023a).

While previous studies found a lower water footprint for insects (Oonincx & de Boer, 2012; Shockley & Dossey, 2014), recent findings challenge this view. Water use varies widely in insect farming, with estimates from 0.003 m^3 up to 11 m^3 per kg (table 3), with a recent review making a best guess at 0.4-0.8 m^3 (Smetana *et al.*, 2023a). This exceeds the water use of beef (0.25 m^3/kg), pork (0.05 m^3/kg), and poultry (0.067 m^3/kg). Note that the methodologies used in different studies vary, making direct comparisons challenging.

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; Vinci *et al.*, 2022; Hunter, 2024). However, these studies also point out that in some cases, insects can have a higher environmental impact on some metrics compared to chicken or even pork, especially under non-ideal climatic conditions in carbon-intensive countries (Sillman, 2021). For instance, mealworms reared on grain-based feed in Canada had the same emissions as chicken (Paris *et al.*, 2024).

The feed conversion ratio (FCR) is also a common indicator for assessing the efficiency of insect feeding and growth. 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 fresh 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).

Table 2. Examples of feed conversion rates (FCR) in insects and conventional livestock. Data reproduced from the review by (Jansson, Hunter & Berggren, 2019).

	FCR (kg feed/kg growth)	**Reference**
Cricket	1.5–3.9	(Lundy & Parrella, 2015; Miech *et al.*, 2017)
Black Soldier Fly	1.7-3.6	(Gligorescu *et al.*, 2020)
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)

Insects generally have a lower FCR than conventional livestock (Table 2). 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% for crickets, compared to 40% in cattle and 55% 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).

3.4. 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, cultivated meat or single-cell proteins. Their goal is to replicate the sensory and nutritional properties of meat while minimising environmental impacts. In a recent review assessing the environmental impacts of different meat substitutes, Smetana, Ristic, et al. (2023c) concluded that, when evaluated on a per-protein basis, insects generally exhibit a lower environmental impact compared to most other alternatives, but are outperformed by plant-based substitutes. In another review that takes into account environmental impact, consumer acceptance, animal welfare and scalability, Bry-Chevalier (2024) found that insect-based products were the least promising of the four categories of alternative proteins considered (plant-based meat substitutes, cultivated meat, single-cell proteins, and insects).

We should keep in mind that direct comparisons between alternative proteins and insect-based options remain rare and the lack of data regarding the environmental impacts of single-cell proteins, cultivated meat or microalgae make these comparisons challenging. Water footprint, for instance, displays widely different results due to varying methodologies. 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 (Upcraft *et al.*, 2021) while other studies consider more processed products that mimic meat texture (Smetana *et al.*, 2023c). This lack of harmonisation can be problematic, as processed products tend to have a larger footprint (Lie-Piang *et al.*, 2021). For example, plant-based meat substitutes have, on average, 1.6 to 7 times higher environmental impact than less processed plant protein sources (e.g., tofu, pulses, and peas) (Santo *et al.*, 2020). Since insects are less likely to gain acceptance and replace meat if consumed whole, at least in Western societies, it is arguably more relevant to consider insect-based processed products when comparing them to meat substitutes.

3.5. 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. Future LCAs should attempt to consider rebound effects to evaluate their extent with quantitative calculations.

Since the environmental footprint of insect protein remains higher than that of many plant-based proteins, discussions on entomophagy risk diverting attention away from the most environmentally sustainable diets focused on plant-based foods (Hodge, 2022). Given these challenges, Shine (2020) questions whether efforts and resources devoted to insect farming might be more effectively used to promote plant-based foods, which are already familiar to consumers.

4. Feed: Environmental impacts of insects compared to conventional feed

4.1. Overview of Life Cycle Assessments

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 in theory be fed with a wide range of wastes, while the yellow mealworm's potential for using waste as substrate is more restricted (Le Féon *et al.*, 2019; Harsányi *et al.*, 2020; Quang Tran *et al.*, 2022; Faes, 2022). As mentioned above, the type of substrate used to feed the insects is the largest determinant of environmental impact.

Table 3 summarises the environmental impacts of insect production compared to soybean meal, compound feed and fishmeal, which are among the most popular feed sources for aquaculture and chicken production. Studies focusing on the use of waste are discussed later (section 8.1). 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.

Table 3: *Environmental impacts of insect-based products compared to common feed sources. Comparison table between a range of LCAs, highlighting the context and limitations of each study, with data from commercial and pilot-scale settings (excluding laboratory contexts). Studies that focus on the use of waste as a substrate are addressed in section 8.1.*

Study and location	**Species**	**Greenhouse gas emissions** *(kg CO2e)*	**Land use** *(m^2)*	**Water depletion** *(m^3)*	**Context**	**Study limitations**
Reference: Soybean meal	NA	2.26 (average deforestation)[a] / 1.06 (no deforestation)[a]	0.062 [a] - 3.26 [b]	0,04 [b]	Kg of product	NA
Reference: Compound feed	NA	1.34 [f]	1.48 [f]	0.018 [f]	Kg of product. Blend of cereals, oilseeds and other ingredients	NA
Reference: Fishmeal	NA	1.15 [a]	0.0052 [a] - 0.6-1.1 [c]	0.35 [d]	Kg of product	NA
Kg of dry matter						
(Smetana *et al.*, 2019) - Netherlands	*H. illucens*	5.3	1.90	0.003	Industrial scale: more than 1000 tons dry larvae annually	High variability in the consequential LCA – less in the attributional one
(Thévenot *et al.*, 2018) - France	*T. molitor*	3.8 [g]	4.10	NA	Pilot: 17 ton larvae annually	Small scale, high energy use in processing
(Roffeis *et al.*, 2020) - Ghana	*H. illucens*	5.5	0.16	11.0	Small scale : 3.5-4.4 tons dry larvae annually	Small scale, use of chicken manure (in addition to brewery waste), warm country
(Kleyn, 2023) - South Africa	*H. illucens*	6.4	2.7	0.2	Small-scale manufacturing : 52 tons of fresh insects annually	Small scale, carbon-intensive electricity grid
(Le Féon *et al.*, 2019) - France	*T. molitor*	2.8	0.66	NA	Simulated system	Simulation based on other studies
(Maiolo *et al.*, 2020) - France	*H. illucens*	3.5	NA	4.71	Simulated system	Simulation based on other studies

(Spykman *et al.*, 2021)	*H. illucens*	5.0 - 11.0	0 - 8.0	-0.003 to 0.19	Simulated system	Simulation based on other studies
Kg of wet matter						
(Oonincx & de Boer, 2012) - Netherlands	*T. molitor*	2.6[g]	3.6	NA	Small scale: 83 tons of fresh insects annually as human food	Small scale, use of fresh carrots in the substrate, slower development cycles than reported elsewhere
(Halloran *et al.*, 2017) - Thailand	*A. domesticus* *G. bimaculatus*	2.3 - 2.6	NA	0.42	Pilot: 36.7 tons of insects annually as human food	Edible insects, outdoors setting in warm country, little automation due to cheap labour
(Suckling *et al.*, 2020) - UK	*G. bimaculatus*	21.1	NA	0.82	Pilot: 12.5 ton wet insects annually for live pet food	Small scale, insects used for live pet food, uncertainties due to the inclusion of frass
Kg of dry protein						
Reference: Soybean meal	NA	4.09[e]	4.34[e]	NA	Kg of protein	NA
Reference : Fishmeal	NA	1.69[e]	0.01[e]	NA	Kg of protein	NA
(Halloran *et al.*, 2017) - Thailand	*A. domesticus* *G. bimaculatus*	4.2	NA	0.71	Pilot: 36.7 tons of insects annually	Edible insects, outdoors setting in warm country, little automation due to cheap labour
(Thévenot *et al.*, 2018) - France	*T. molitor*	5.77[g]	6.35	NA	Pilot: 17 ton larvae annually	Small scale, high energy use in processing
(Mungkung & Phetcharaburanin, 2023) - Thailand	*A. domesticus*	4.6 (frozen) - 11.3 (powder)	NA	NA	Average of 36 small-, medium-, and large-sized farms	Edible insects, outdoors setting in warm country, little automation due to cheap labour
(Dreyer *et al.*, 2021) - Austria	*T. molitor*	20.4	22.38	NA	Small-scale production	Edible insects, small scale, use of organic feedstuff
(Nikkhah *et al.*, 2021) - South Korea	*Protaetia brevitarsis seulensis*	8.05 - 12.52	NA	NA	Small-scale edible insect production unit: 1 ton per year	Very small scale, uncommon species

(Paris *et al.*, 2024) - Canada	*T. molitor*	14.94	NA	NA	Grain-based feed scenario. Small scale producers.	Small scale, chicken feed as a substrate (using food waste has a lower impact), clean energy grid
(Bosch *et al.*, 2019) - Netherlands	*H. illucens*	4 - 7	11 - 93	NA	Control diet scenario. LCA using data from 40 other studies	Based on other studies
(Bosch *et al.*, 2019) - Netherlands	*H. illucens*	3 - 19	3 - 67	NA	Range for 27 substrates. LCA using data from 40 other studies	Based on other studies
(Spykman *et al.*, 2021) - Various	*H. illucens*	12 - 24	-1 to 18	– 0.007 to 0.39	Simulated system with 4608 production scenarios	Simulation based on other studies

"NA" denotes that a study did not include this particular outcome variable in its LCA.

Notes: [a] ECOALIM database (Wilfart et al., 2016) - Uses the land competition metric (m²) - Average for a kg imported in France - Fishmeal is from Peru, soybean meal from Brazil ; [b] Ecoinvent 3 and Agrifootprint databases; [c] (Samuel-Fitwi et al., 2013); [d] Danish LCA Food Database ; [e] (Thévenot et al., 2018) using data from the ECOALIM database ; [f] (Smetana et al., 2023a) using data from the Agri-footprint database ; [g] When reproducing the results of these studies, Modahl and Brekke (2022) found an increase in land use and CO2e emissions averaging 20 percent compared to the original results.

As shown in table 3, reported environmental impacts can vary significantly, sometimes tenfold or even a hundredfold, depending on species, substrates, energy sources, methodologies, scope and geographical location (Liverød, 2019; Smetana *et al.*, 2023c). Likewise, environmental impact estimates for conventional feed also vary.

Regarding climate impact, insect meals generally have higher CO2 emissions than soybean and fishmeal, with emissions for insect meals ranging from 2.8 to 11 kg CO2e per kg of dry matter, 2.6 to 21.1 kg CO2e per kg of wet weight, and 3.0 to 24.0 kg CO2e per kg of protein. Some values are significant outliers due to specific contexts, such as the live pet food industry (Suckling *et al.*, 2020). In contrast, soybean meal emissions average between 1.06 and 2.26 kg CO2 per kg of product, while fishmeal remains relatively low, averaging around 1.15 kg CO2.

Land use estimates also differ, ranging from 0.16 to 8.0 m² per kg of dry insect product. In comparison, soybean meal required 0.062 to 3.26 m² per kg of product, depending on deforestation and the use of the land competition metric. Regarding energy use, studies also show mixed results and tend to follow the same pattern as GHG emissions. For instance, a recent estimate for the most efficient insect farming methods in Europe ranged from 0.36 to 21.2 MJ per kg of insects, with the lowest values achieved when waste substrate is used (Smetana *et al.*, 2023a). By comparison, producing one kilogram of compound feed requires approximately 5.81 MJ.

Data for insect production is less consistently reported across studies, but water use in insect production shows the most variation, from as low as 3 litres (0.003 m³) to 11 m³ per kg of product. A recent review by Smetana et al. (2023a) suggests that insect farming generally has a higher water footprint than compound feed, with insects requiring between 0.4 and 0.8 m³ of water per kg compared to 0.0179 m³ for compound feed. More generally, methodologies for calculating water footprint are still evolving and may not always provide wholly accurate results (Smetana *et al.*, 2023a). The substrate for feeding insects was a major driver of water consumption, especially if insects were fed crop products (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).

Additionally, most studies overestimate the protein content of BSFL, mealworms, and crickets (Janssen *et al.*, 2017b; EFSA *et al.*, 2024), leading to an underestimation of their environmental impact per kg of protein (Modahl & Brekke, 2022). This error arises because the standard nitrogen-to-protein conversion factor (6.25), commonly used for most foods, is not appropriate for insects due to their non-protein chitin content. For insects, the accurate conversion factor is 4.76. When Modahl and Brekke (2022) reproduced the findings of some of the most cited LCAs (Oonincx & de Boer, 2012; Thévenot *et al.*, 2018), they reported increases in land use and CO2e emissions exceeding 20% compared to the original results.

Overall, while results vary, most LCAs indicate that insect-based feeds have higher GHG emissions than fishmeal or soybean meal when waste is not used as a substrate. Regarding land use, most LCAs show higher impacts than fishmeal and, depending on the metric, soybean meal. Water use results are mixed, but a slight majority of studies indicate that soybean meal and fishmeal have lower impacts than insect meal. Insects reared on non-utilised waste streams tend to have lower environmental impacts across all metrics, although this might not be the case depending on the substrate (see section 8.1).

Note that due to nutritional limitations, insect meal can only replace a fraction of conventional animal feed, not the entirety, and mostly acts as an additive (Gasco *et al.*, 2023; Hamam, D'Amico & Vita, 2024). Recommended inclusion levels of insect feed are up to 25% to 30% for fishmeal and 10% in chicken and pig feed, leaving the environmental impact of the rest unchanged (Gasco *et al.*, 2023). Exceeding these limits can lead to reduced protein digestibility. Research on inclusion rates for shrimp feed (10% to 30%) is ongoing (Gasco *et al.*, 2023).

4.2. Aquaculture: Environmental impacts of insect meal as aquaculture feed

The use of insects as feed in animal aquaculture is a growing practice that is expected to account for a significant portion of the insect market in the coming years.

Aquaculture is a rapidly expanding market driven by growing world population and demand for seafood, accounting for 46% of seafood production in 2018 (FAO, 2020; Quang Tran *et al.*, 2022). With forage fish stocks declining, finding environmentally sustainable feed options is a challenge for aquaculture, to which insect farming is presented as a solution (Froehlich *et al.*, 2018; Jannathulla *et al.*, 2019). Plant-based feeds like soy meal are increasingly used as fish feed, but 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 insect aquafeed as a new protein source. Overall, they found that while insect meals show benefits in terms of forage fish depletion (compared to fishmeal) and land use (compared to soy meal), these insect meals exerted 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.

More precisely, studies showed differences in data sources, fish diet formulations, and the proportions in which the diets were modified. 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. On another aspect, 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).

Recent studies have reached similar conclusions. A LCA in South Africa found that insect meal had a greater environmental impact than fishmeal across nearly all metrics, with CO2 emissions being two to three times higher (Kleyn, 2023). A 2023 LCA in Norway reported that while BSFL meal performed better than soymeal when reared on compost, using wheat bran and dairy waste as substrate—more representative of industry practices—resulted in greenhouse gas emissions twice as high (Zlaugotne *et al.*, 2023). While BSFL had similar land use to soymeal, it consumed more energy and water. Yellow mealworm protein had an even worse environmental performance across these metrics (Zlaugotne *et al.*, 2023). In a comparative LCA of aquaculture systems in Singapore, insect-based meal had "higher environmental impacts than fishmeal and soybean meal for most impact categories," even though the model "reduced electricity and water use to factor in technology optimization until 2040" and assumed "a replacement of part of the feed by food waste" (Bohnes & Laurent, 2021).

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. It's important to consider that these insect-based products are still in their early development stages. Compared to poultry by-product meal and microalgae, two other emerging aquafeed options, insects generally require less "emergy," reflecting lower total energy investment (Maiolo *et al.*, 2021). Future innovations and scaling up production, along with setting appropriate environmental targets, could potentially reduce their environmental impacts.

In contrast, a study on aquaculture in Norway found more positive results for insects (Modahl & Brekke, 2022). When insects were fed high-value ingredients, such as grain or bran commonly used by major companies, their environmental impact was similar to that of conventional fish feed ingredients like soy, wheat, or faba beans. They also suggest that the environmental impact of insect meal could be greatly reduced by using lower-value feed ingredients, such as distiller's dried grains with solubles or cookie residues. In these cases, the environmental footprint of insects was similar to that of blue whiting protein, a type of fishmeal used in Norway. Some elements can explain this discrepancy. First, the study used a CO2 emission estimate of 15 kg per kg of protein for soybean meal, which is considerably higher than the 3.13 to 6.99 kg per kg of protein reported in other research (Hörtenhuber *et al.*, 2014; Thévenot *et al.*, 2018; Tallentire, Mackenzie & Kyriazakis, 2018; Vauterin *et al.*, 2021). Second, Modahl and Brekke (2022) model side-streams using economic allocation, with low-value substrates being assigned lower environmental impact. This may overlook factors like the low nutritional value of waste leading to extended production cycles and increased energy consumption (Beyers *et al.*, 2023).

More broadly, studies that find significant sustainability benefits for insect farming often focus on systems that utilise waste and non-used side-streams as feed substrates (Röthig *et al.*, 2023). These studies also underscore the advantages of using locally sourced substrates, as cargo transportation is a major contributor to GHG emissions in fishmeal production (Mertenat *et al.*, 2019). The implications of using low-value vegetables and waste as insect feed are discussed further in section 8.1.

In comparison, 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.

In another comparative study, increasing fishmeal and fish oil production from trimmings and using marine fish in near-shore sea cages were found to have a significantly lower impact than insect-based meal (Bohnes & Laurent, 2021). Other strategies can help reduce the environmental impact of future fisheries by making fishmeal more sustainable. 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).

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).

4.3. Environmental impacts of insect meal as a conventional livestock feed

Few studies focused on the impacts of insects as chicken feed specifically, although it is estimated to be the third largest portion of the insect market in the future (de Jong & Nikolik, 2021). Vauterin et al. (2021) assessed the potential of insect-fed broiler chickens for meat production in Europe. Reviewing different LCAs and applying their results to broiler production, the study found that broiler chickens fed insects reared on grain-based industrial feed had higher GHG emissions than those fed soybeans (25.82 vs. 18.50 kg CO2e per kg of protein). Emissions varied widely, with maximum levels for insect-fed chickens reaching 75.14 kg CO2e, while waste-fed insects averaged a minimum of 10.65 kg CO2e. One limitation of the study was that it averaged data from a diverse range of studies and species, not limited to optimal scenarios, leading to some very high estimates of carbon emissions.

In comparison, pig feed is projected to be a fairly small part of the market (de Jong & Nikolik, 2021; Pexas & Kyriazakis, 2023). The impact of insect feed on ruminants, like cows or sheep, is not explored in depth, as these animals are not expected to become a major market for insect-based feed (IPIFF, 2021; Ahmed & Nishida, 2023).

A more promising path would be to improve 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 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). Increasing domestic production of soy and maize in the EU is also a promising option (Ryba, 2024). Opting for certified soybeans from regions not associated with deforestation has been posited to result in a 47% to 53% reduction in the GHG emissions associated with soybean meal (Hörtenhuber *et al.*, 2014; Wilfart *et al.*, 2016; Vauterin *et al.*, 2021). The transition towards sustainable soybean production holds the potential to substantially decrease greenhouse gas emissions, surpassing the potential impact of transitioning to insect-based feeds.

5. 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% of the total market of insects raised for food and feed (de Jong & Nikolik, 2021; Sogari *et al.*, 2023b). Given its large size, minimising environmental impact is a critical concern in the insect pet food market. However, we only managed to find one study, Bosch and Swanson (2021), extensively exploring the environmental aspects of insect-based pet food production. Several other papers discuss this topic, but they typically compare the environmental impact of insects to meat rather than directly to pet food or meat co-products (Bram, 2021; Schaap, 2021; Abd El-Wahab *et al.*, 2021; Duijnisveld & Myriam, 2022; Ahmed, İnal & Rïaz, 2022; Valdés *et al.*, 2022). Other studies briefly mention the potential of insects in pet food but lack detailed analysis. For instance 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. Several sustainability claims originate directly from the industry. Beynen (2018) reviewed 12 insect-based pet food products 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). These co-products have a comparatively low environmental impact and are similar to the food waste some have 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 and have low economic value. While some studies suggest that pet food has a high environmental impact (Okin, 2017; Su, Martens & Enders-Slegers, 2018), they often incorrectly assume that meat is the primary protein source. Moreover they “do not provide reference data on the impact of these conventional pet food ingredients”, complicating direct comparisons (Bosch & Swanson, 2021).

Bosch and Swanson (2021) concluded that, on average, insect proteins for pet food emit two to ten times more GHG than conventional pet food products. They refer to a Blonk Consultants report, which estimates the carbon footprint of pet food at “about 1 kg CO2e 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 to 24 kg CO2e by kg of protein (see table 3).

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.

Additionally, comparing insects with other alternatives is essential. Plant-based pet foods are sometimes estimated to 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, 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 true for insect diets; data on the nutritional quality and digestibility of insects is less documented, with limited available data (Bosch *et al.*, 2014; McCusker *et al.*, 2014; Mouithys-Mickalad *et al.*, 2020; Acuff *et al.*, 2021)

6. Environmental impacts of frass

For the purposes of this paper, "frass" refers to a residue left by insect farming, consisting of excrements, leftover substrate, and insect body parts (European Commission, 2021). 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. The use of frass is central to the claims that insects can contribute to a circular economy, allowing the recirculation of nutrients (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.

To date, frass as a fertiliser has not taken off (Jasso *et al.*, 2024). 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).

Frass contains high quantities of both macro- and micronutrients—especially nitrogen, phosphorus, and potassium—offering advantages over synthetic fertilisers that typically supply only macronutrients (Houben *et al.*, 2020; Watson *et al.*, 2021b; Jasso *et al.*, 2024; Siddiqui *et al.*, 2024a; Zunzunegui *et al.*, 2024). Antimicrobial peptides naturally present in BSFL can act as a defensive barrier for the plant (Basri *et al.*, 2022). Containing beneficial microbes, frass can enhance plant resilience to stressors like flooding and disease, acting as a form of biological pest control (Poveda, 2021; Barragán-Fonseca *et al.*, 2022; Beesigamukama *et al.*, 2023) For instance, the chitin in *T. molitor* frass triggers defences against Fusarium wilt disease (Quilliam *et al.*, 2020). Frass also contains nitrogen-fixing bacteria that increase nitrogen uptake in the plant, promoting plant growth (Siddiqui *et al.*, 2024a). It is readily absorbed by plant roots, returning carbon, nitrogen, and ammonium to the soil and decomposing faster, which enhances soil quality more quickly (Houben *et al.*, 2020; Poveda, 2021; Jasso *et al.*, 2024). Frass's composition resembles chicken manure.

Due to the diverse substrates used in insect farming and lack of standardisation, frass exhibits considerable variability in its nutritional composition and microbial diversity, resulting in environmental impacts that can vary widely and nutrients that may not meet the nutritional needs of particular crops (Schmitt & de Vries, 2020; Gebremikael *et al.*, 2020; Poveda, 2021; Zunzunegui *et al.*, 2024). Further research is necessary to fully understand frass's capacity to enhance crop productivity and soil health, identify optimal characteristics and inclusion levels, and identify whether frass can be a comprehensive replacement for organic fertiliser (Bloukounon-Goubalan *et al.*, 2021; Jasso *et al.*, 2024; Zunzunegui *et al.*, 2024). Although frass has a role in high-value woody crops or horticultural crops, currently "its use in extensive crops is far from being possible" due to lack of research (Zunzunegui *et al.*, 2024).

Some studies note negative effects on soil processes, such as excessive nitrite accumulation in the soil (Watson, Preißing & Wichern, 2021a) or inhibited seed germination (Kawasaki *et al.*, 2020). While several studies indicate that frass can increase yield, others “reported negative growth associated with plausible phytotoxicity of the frass” (Kagata & Ohgushi, 2012; Alattar, Alattar & Popa, 2016; Berggren *et al.*, 2019; Lopes, Yong & Lalander, 2022). High moisture content in substrates used for BSFL rearing—such as food waste—often leads to immature, wet frass with high ammonium levels and low porosity, causing ammonia poisoning that hinders plant growth, and complicating processing and handling (Alattar *et al.*, 2016; Cheng, Chiu & Lo, 2017; Lalander *et al.*, 2020; Siddiqui *et al.*, 2024a). However, reducing moisture could lead to slower BSFL growth (Siddiqui *et al.*, 2024a). BSFL frass lacks optimal nutrient availability for promoting robust plant growth—especially in supporting extended root development—which reduces plants' ability to access nutrients from deeper soil layers, potentially impacting overall growth and yield (Gebremikael *et al.*, 2022).

There is a lack of research on the impacts of frass on the environment, especially as most existing studies are done in labs with limited insights into long-term impacts (Siddiqui *et al.*, 2024a). Some research shows a positive impact, indicating that frass lowers the environmental impacts of insects as food and feed by providing an additional product (Siegrist *et al.*, 2023). Some studies indicates that using frass can reduce CO2 emissions by 12-16% compared to mineral fertilisers (Thévenot *et al.*, 2018; Modahl & Brekke, 2022), and may lower emissions of CO2, NH3, CH4, and N2O compared to compost (Pang *et al.*, 2020; Song *et al.*, 2021).

Smetana et al. (2019) found superior results for insect frass over other organic fertilisers, e.g., 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). However, Schmitt and de Vries (2020) “nuanced this conclusion by suggesting that environmental impacts need to use comparable fertilizing units as a baseline,” while “the macronutrient, micronutrient and pathogen contents, as well as the greenhouse gases produced during the process, are highly dependent on the inputs used to produce the fertilizer and the amendment" (Schmitt & de Vries, 2020; Walling & Vaneeckhaute, 2020; Hénault-Ethier *et al.*, 2024). Meanwhile, it "remains to be seen whether insect frass… has a lower environmental footprint than conventional farm manures" (Hénault-Ethier *et al.*, 2024). A study on organic liquid fertilizer derived from waste-fed insect frass found GHG emissions to range from six times higher to four times lower than conventional fertilizers, depending on nitrogen losses (Desaulniers Brousseau *et al.*, 2024).

Another 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; Beesigamukama *et al.*, 2023). 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).

A complicating factor is the EU's required disinfection process by which all frass must be treated at ≥70°C for one hour to avoid contamination. Heating the frass has a few undesirable effects, including killing most or all of the beneficial microbiota and destroying biomolecules that enrich soils (Poveda, 2021; Zunzunegui *et al.*, 2024). That said, contamination is a serious issue (Food and Agriculture

Organization, 2021). When insects are fed with waste, there's a risk that frass could contain pathogenic microorganisms (Basri *et al.*, 2022). A recent review identified high levels of contamination in larvae and frass across various substrates (such as cereals, fruits, vegetables, and agri-food co-products) with pathogens, including *Salmonella spp., Xanthomonadaceae, Staphylococcus aureus, Clostridium perfringens, Escherichia coli*, and *Bacillus cereus* (Wynants *et al.*, 2019; Kawasaki *et al.*, 2020; Brulé *et al.*, 2024). Methods of sterilising substrate have been shown to curtail the productivity of BSFL rearing and may undermine the benefits of frass when used as a fertiliser (Gold *et al.*, 2020; Siddiqui *et al.*, 2024a). However, few studies have been performed on treated frass (Zunzunegui *et al.*, 2024).

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 Australia, the current price of frass is significantly above what farmers are willing to pay (Kragt, Dempster & Subroy, 2023). It currently costs between $1,500 and $3,000 per tonne depending on specifications, significantly higher than compost and manure at $300–$350 per tonne (Kragt *et al.*, 2023). 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).

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).

More data is needed to fully understand the wider impacts of frass, especially treated, before it can be considered a viable contributor to a circular economy (Watson *et al.*, 2022).

7. Impacts on biodiversity and zoonotic diseases

7.1. Biodiversity threats and invasive species

An environmental issue shared by both insects as food and feed concerns impacts on local biodiversity. Farmed insects, if released into natural environments, could pose risks by adversely affecting local insect populations. There is a risk that farmed insect species may escape, potentially disrupting local natural ecosystems through competition with native species or by introducing harmful genes into wild populations (Yen, 2015; Halloran *et al.*, 2018; Wilderspin & Halloran, 2018; Lourenço *et al.*, 2022; Siddiqui *et al.*, 2024b). Research indicates that genes selected for farmed colonies have already been transferred to wild BSFL populations in Europe (Generalovic *et al.*, 2023). This precaution is less relevant to yellow mealworms which are mostly found in stored goods, where they are considered a grain pest, although they are considered invasive in Moldova (Lourenço *et al.*, 2022).

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". Even in high-income countries, "the biosecurity status of these rearing facilities is worrying", with a "frequent and high numbers of escapees" and a lack of regulatory policy guidelines (Bang & Courchamp, 2021). This can be the case even for globalised species that are not granted invasive status, like the BSFL. In another concerning example, an examination of insect-based protein bars purchased online revealed that some contained larval-stage insect pests, which could contribute to the spread of invasive species (Giusti *et al.*, 2024).

Past instances of invasive insect species include Africanised bees, commonly known as "killer bees", and the spongy moth (*Lymantria dispar dispar* Linnaeus). Africanised bees originate from East African lowland honey bees (*Apis mellifera scutellata* Linnaeus) brought to Brazil for a cross-breeding experiment with European 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 the spread of hybrids to other South American nations, Central America, Mexico, and the USA. Similarly, spongy moths 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).

In the EU, risk assessments have been conducted prior to authorising new insect species on the market; however, these assessments have primarily taken place in Northern countries, with risk evaluation for Southern regions largely missing (Lourenço *et al.*, 2022). While some species, like the black soldier fly, were initially considered unlikely to establish in the wild (Spranghers *et al.*, 2017), more recent evidence reached a contrasting conclusion (Roháček & Hora, 2013; Jonsell, 2017). So far, gene mixing between domesticated and wild BSFL populations is not widespread in non-native areas. However, near BSFL farms and research centres, increased mixing may disrupt local genetic adaptations, posing a threat to native populations. More competitive domesticated strains could invade new and existing habitats due to human activities (Kaya *et al.*, 2021). 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).

Furthermore, high-density insect farms expose insects to various diseases and pathogens, including novel strains (Weissman *et al.*, 2012; Jansson *et al.*, 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. 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 topic of diseases in insect farming is addressed in more detail in section 7.2.

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 improved insect strains using genetic edition 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 with 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).

One potential risk-management strategy could involve genetically modifying insects to prevent their spread in the wild. Extensive research has been conducted on this topic to control pest populations, such as disease-carrying mosquitoes or moths, by reducing their reproductive capacity and making them infertile (Waltz, 2017; Teresa *et al.*, 2018; Devos *et al.*, 2022). Research specifically on farmed insects is limited, highlighting the need for further studies and appropriate regulatory frameworks.

Jansson et al. (2019) propose a conservative approach to insect farming in Sweden, recommending the exclusion of non-native species in food and feed production systems. This stance, rooted in the precautionary principle, is further supported by Berggren et al. (2019), who advocate for the use of non-native species only when substantiated by robust scientific evidence of safety.

This restrictive guideline presents several implications for the insect farming industry. The limitation on available species may constrain producers' ability to optimise efficiency, potentially increasing the environmental footprint of insect farming operations. Such restrictions could have significant economic ramifications, potentially hampering industry growth and competitiveness. Implementation of these constraints would necessitate the development of a dedicated legal structure, likely impeding industry growth. Without compensatory measures, such as targeted incentives or penalties on established industries, these constraints might impede the dissemination of innovations within the sector. This cautious approach, while aiming to safeguard ecological integrity, presents a complex trade-off between environmental precaution and industry development.

7.2. Zoonotic diseases and antibiotic use

Another environmental issue shared by both insects as food and feed concerns disease management. 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). There is also a 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; 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; Aidoo *et al.*, 2023).

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).

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.*, 2023). The use of antibiotics in insect farming and its impact on antimicrobial resistance remains uncertain as it is unclear whether this would be effective or desirable, considering the risk of antimicrobial resistance (Suckling *et al.*, 2020). Nonetheless, 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."

8. Future possible improvements

8.1. Environmental impacts of feeding insects with waste

The utilisation of food waste as a substrate for insect farming is frequently suggested as a prospective solution to improve the environmental potential of insects and enhance the circularity of the food system (Madau *et al.*, 2020; Rehman *et al.*, 2023).

It is noteworthy that a majority of existing insect farms makes little use of food waste, partially due to regulatory constraints that prohibit the use of certain proposed waste products on the grounds of public health regulations, as well as logistical and economic constraints (Salemdeeb *et al.*, 2017; Skrivervik, 2020; Ffoulkes *et al.*, 2021; Sillman, 2021; Mancini *et al.*, 2022; Fischer, 2022; Biteau *et al.*, 2024b). 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 livestock feed. In contrast, BSFL is more adaptable and capable of consuming a broader array of food waste.

Some substrates discussed in this section have not received regulatory approval. In the UK and EU, permitted waste products and by-products are limited to processing waste and former foodstuffs consisting solely of vegetal, dairy, egg, and/or honey origins, as laid out in the EU Regulation 2022/1104. In the US, the BSFL, the sole insect authorized for animal feed, must be "raised on a feedstock composed exclusively of feed-grade materials" (Association of American Feed Control Officials, 2021). Due to safety concerns, substrates incorporating manure or mixed waste materials are restricted. These substrates are mentioned here in the context of potential future improvements, although they may not receive regulatory approval in the foreseeable future.

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 scarcity of studies and the lack of industrial-scale research make it challenging to predict how these findings would scale up. A 2022 review focusing on BSFL found a lack of data on emissions, and that the absence of robust guidelines and protocols complicates comparisons across studies (Van Peer *et al.*, 2022). For instance, while rearing conditions significantly affect emissions, the specific details are often inadequately reported in studies, and nearly every experiment is employing a different protocol (Deruytter *et al.*, 2022). GHG emission estimates for BSFL farming differ by a factor of up to 12 between studies (Jensen *et al.*, 2021).

The use of food waste as feed can significantly change GHG emissions, with estimates ranging from a beneficial -6.42 to 5.3 kg CO_2e for a kg of insect meal (Smetana *et al.*, 2019; Bosch *et al.*, 2019; Ites *et al.*, 2020; Boakye-Yiadom, Ilari & Duca, 2022; Pahmeyer *et al.*, 2022; Johansson, 2023; Elsayed *et al.*, 2024). The negative value (-6.42 kg CO_2e) 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.

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 compared to a standard waste treatment. 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 (Spykman *et al.*, 2021). 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).

Rearing insects on waste can improve certain environmental metrics while negatively impacting others. A German study found that a diet with three-quarters BSFL fed on organic and peeling waste used 80% less water and 90% less land, but required 50% more energy and produced five times the GHG emissions compared to conventional trout feed (mainly fish meal, fish oil, and soy meal) (Goyal *et al.*, 2021).

While feeding insects with manure presents potential environmental benefits, a review of 75 BSFL production systems revealed contradicting results, with outcomes varying significantly based on factors like BSFL strain (Grassauer, Ferdous & Pelletier, 2023). Additionally, since most of these systems are micro-scale (i.e., laboratory settings), they provide limited insights applicable to large-scale production. For instance impacts range from 0.77 to 12 kg CO_2e per kg of dried insects (Roffeis *et al.*, 2017) and 1 to 7 kg CO_2e per kg of proteins (Bosch *et al.*, 2019), and this benefit can be negated by the loss of efficiency in the production process (Smetana *et al.*, 2016) . Another study indicated that it remains unclear whether composting pig manure is more beneficial with or without insects, as the environmental impacts vary depending on the specific impact category assessed (Beyers *et al.*, 2023). However, when insects are reared on manure, ammonia and methane emissions can be considerable (Van Peer *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 can outperform BSFL on global warming potential and energy consumption (Mondello *et al.*, 2017; Mertenat *et al.*, 2019; Ites *et al.*, 2020; Kim *et al.*, 2021; Nugroho *et al.*, 2023; Ferronato *et al.*, 2024). Emissions from treating a ton of biowaste with insects range widely, from -432 kg CO2e (indicating a net benefit) to 877 kg CO2e, with an average of 70 kg CO2e across 12 LCAs

(Salomone *et al.*, 2017; Smetana *et al.*, 2019; Boakye-Yiadom *et al.*, 2022). Although these are encouraging findings, insects do not always surpass traditional waste treatment, animal feed, or biodiesel options (Frasnetti, Sadeqi & Lamastra, 2023). This variability stems from differences in system boundaries; studies reporting low emissions often exclude processes like substrate collection, larvae production, pre-treatment and transport (Komakech *et al.*, 2015; Guo *et al.*, 2021), whereas higher values (up to 877 kg CO2e) account for facility construction, frass processing and larvae production (Smetana *et al.*, 2019; Boakye-Yiadom *et al.*, 2022).

In terms of transport, some studies have shown that including the transportation of feed substrates in a life cycle assessment (LCA) can increase CO2 emissions and energy consumption by up to 67% (Liverød, 2019; Ites *et al.*, 2020). Some researchers advise that the substrate's geographical origin is important for insect production's environmental and socioeconomic performance (Roffeis *et al.*, 2020; Ferronato *et al.*, 2024), and "locally available by-product streams should be preferred"(Derler *et al.*, 2021; Adamaki-Sotiraki *et al.*, 2024). However, other findings indicate that transport may have only a minor effect, accounting for less than 4% of total emissions (Modahl & Brekke, 2022).

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; Modahl & Brekke, 2022; Athanassiou *et al.*, 2024).

Furthermore, conventional livestock can also consume some waste products. Nearly 30% of global livestock feed intake consists of agricultural co-products, byproducts, and food-processing residuals (Mottet *et al.*, 2017; Dou, Toth & Westendorf, 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) with lower environmental impacts than anaerobic digestion (Shurson, 2020). Notably, some substrates mentioned previously 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; Verkuijl *et al.*, 2024). By competing with products that would otherwise be used as pig or poultry feed, insect farming may even intensify pressures on arable land (Verkuijl *et al.*, 2024).

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. Despite the common assumption that it is more sustainable to feed insects materials unsuitable for conventional livestock (Smetana *et al.*, 2019; Modahl & Brekke, 2022), this may not always hold true (Spykman *et al.*, 2021). A LCA found that producing BSFL meal from non-utilised side streams that are typically reincorporated into fields or left to decompose had environmental impacts 10 to 100 times greater than those of soybean meal or fishmeal in terms of greenhouse gas emissions, water use, and energy consumption (Beyers *et al.*, 2023). While the residues themselves had a low environmental impact, their limited nutritional value delayed larval maturation, extending the production cycle and increasing energy use; they also required more feed and yielded a less favourable nutritional profile (Spykman *et al.*, 2021). To achieve suitable nutritional levels, it was necessary to supplement the residues with higher-value agricultural products. Consequently, the feed conversion ratio (FCR) of BSFL ranges between 4.6 and 10 when fed on manure and residues, compared to 1.4–2.6 on artificial feed (Rehman *et al.*, 2023).

Comparative studies on the environmental impacts of waste-fed insects versus waste-fed farm animals are scarce. A WWF study assessed three food-waste-to-feed pathways for egg production: food waste converted into BSFL meal for hens, processed food waste fed directly to hens, and bakery by-products fed to hens (McBride *et al.*, 2021). Results were mixed, with BSFL meal having significantly higher impacts than the baseline in global warming potential and water consumption, but requiring less land. While using renewable energy reduced carbon footprints by 0.1% to 51%, BSFL-based diets still had higher GHG emissions than the baseline and other food waste-based diets even with these improvements.

Table 4. 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	*0%*	*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%

8.2. Other levers to improve insect farming’s sustainability

A comprehensive assessment of insect farming's potential necessitates consideration of prospective improvements in production 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). Small-scale systems tend to be less sustainable than larger ones, although scale played a comparatively much smaller role compared to key factors such as heating and substrate type (Pahmeyer *et al.*, 2022).

Ferronato et al. (2024) observed that overall environmental impact could be reduced by extending equipment lifespan by 15 years, and using products close to the treatment facility, as well as cutting energy use by 50% and stopping reliance on fossil energy. Switching to renewable energy is crucial to reduce GHG emissions (Maiolo *et al.*, 2021), although “it is unlikely that on-site renewables will be a solution for all insect producers” (Smetana *et al.*, 2019). Furthermore, transitioning to renewable energy would benefit all livestock feed production methods, so insect farming would not hold a distinct advantage in this regard (Paris *et al.*, 2022; Ryba, 2024).

The use of waste heat from other industries for insect facilities may reduce energy usage (Reyes-Lúa *et al.*, 2021). For instance, data centre excess heat has been used to provide high temperatures to mealworm farms (Vesterlund, Borisová & Emilsson, 2024). It showed promising results, although reductions in CO2 emissions and kwH were not quantified. Industrial symbiosis, where insect farms collaborate with other industries to utilise waste streams, also shows potential (Haq, Välisuo & Niemi, 2021). Of course, relying on industrial symbiosis will naturally curtail the available options for the insect industry to locate and build new sites. Of the processing methods, in a recent study, "FOP (freezing–oven drying–hot pressing) showed the best environmental performance in terms of all selected impact categories except water use, while the BOS (blanching–oven drying–SFE with CO2) group had the highest environmental impacts in all categories" (Cámara-Ruiz *et al.*, 2023).

One potential solution to mitigate the environmental impact of heating is to use frass (insect waste) in biogas plants. This strategy proposes a circular energy model where frass is used to generate biogas, with the resultant exhaust heat redirected to maintain optimal temperatures in rearing facilities (Wedwitschka, Gallegos Ibanez & Jáquez, 2023; Abubakar *et al.*, 2023). The economic viability and real environmental contribution of this practice is still under investigation.

Several innovations are being explored to reduce environmental impacts, such as Pulsed Electric Fields, a pre-treatment more energy-efficient than blanching (Hajj, 2023). Some studies explore the use of insect-based milk, which has lower environmental impact than bovine and soy milk, and a similar impact to almond and oat milk (Tello *et al.*, 2021). It is likely, however, to face similar consumer acceptance issues as other insect food products. Others explore lab-grown insect meat, with similar benefits and challenges compared to normal insect meat substitutes, although energy consumption could be higher (Siddiqui *et al.*, 2024b). Regarding insects for human consumption, some studies suggest integrating the cost of externalities into the price of food, making insects more competitive than some animal products (Xu & Milana, 2024).

Another beneficial approach could involve supplementing fish or livestock diets with antimicrobial peptides (AMPs) naturally found in insects, which help protect against diseases and strengthen the immune system (Xia, Ge & Yao, 2021). Even small amounts of BSFL AMPs have been shown to reduce fish mortality (Zhang *et al.*, 2024).

Some studies explore genetic selection and modification in insects as a potential path toward improved sustainability (Athanassiou *et al.*, 2024). Unlike conventional livestock, research on the genetics of BSF is still in its early stages, with limited genomic resources available. Although insects are already efficient, Dossey et al. (2022) highlight how gene editing in crickets could enhance growth rates or reduce mortality and disease. In terms of artificial selection, one study showed increased larval weights in BSF, though it had no significant effect on feed conversion ratio or GHG emissions, while noting possibilities for future improvements (Facchini *et al.*, 2022). The success of genetically modified insects will depend on public acceptance; early GMO companies, confident in the environmental benefits of genetic modification for crops and livestock, underestimated the impact of public backlash (Mohorčich & Reese, 2019; Food and Agriculture Organization, 2021; Ryba, 2024).

While various insect-derived coproducts—such as lipids, chitin, pigments, nanochitin, chitosan, protein extracts, bioactive peptides and biofuel—are under investigation (Ravi *et al.*, 2020; Moruzzo *et al.*, 2021; Röthig *et al.*, 2023; Hasnan *et al.*, 2023), they fall outside the scope of this paper, which focuses on insects as food, feed, and fertilizer. These coproducts are still in the early stages of development, with limited environmental data available, warranting further research.

9. 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 or eco-friendly insulation materials.

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. However, insect proteins tend to be considerably more expensive than fishmeal and this price disparity might persist in the future (de Jong & Nikolik, 2021).

The most extensive available model on the costs of production comes from Leipertz et al. (2024) and finds that, due to costs, "insects will likely not be part of mass farm animal feed in the near future." Their default scenario for production in the Netherlands gives a production price for defatted larvae meal of 5,116 EUR per ton of dry matter (approximately 5,500 USD). Industry partners with whom the authors collaborated agreed that this model was plausible. This price is significantly higher than the competitive price point needed to rival conventional protein sources like fishmeal, which is around 1,296 EUR (1,400 USD).

Leipertz et al. also explore future scenarios, concluding that simply improving production processes and parameters will not suffice to make insect farming cost-competitive with fishmeal. They suggest that profitability might be achieved by selling frass at a high price or by acquiring feeding substrates at very low costs, such as waste. However, they deem these conditions unrealistic for mass production (Leipertz *et al.*, 2024). Other studies also find significant barriers to economic competitiveness (Megido *et al.*, 2024;

Biteau *et al.*, 2024a), and a good nutritional profile is not enough for making insects a large part of sustainable aquaculture (Panteli *et al.*, 2024).

A series of interviews with insect rearing experts indicate that “currently the insect industry is not able to offer many economic, environmental or social values”, and that barriers such as food acceptance or regulation need to be overcome before creating positive impact (Bijvoet, 2022). Given these challenges, the IPIFF (International Platform of Insects for Food and Feed) recently said that it “does not claim to replace soy or fish meals used in conventional farming but rather to offer a complementary product for certain farmers, at a premium price justified by its high content of proteins, vitamins, and minerals” (Playoust-Braure, 2024). If insect meal is just a complement, this puts into question the claims that it could significantly reduce the pressures on marine biodiversity and deforestation.

Economic challenges are also present in other markets. Although pet food is the most profitable market segment, this is because it targets premium consumers, such as those seeking hypoallergenic ingredients, and who are willing to pay higher prices (de Jong & Nikolik, 2021). Insect frass is priced 4 to 10 times higher than other organic fertilizers, such as compost and manure (Kragt *et al.*, 2023). Finally, as meat substitutes, insect-based products are more expensive than most alternatives (Malila *et al.*, 2024), facing significant price penalties (Michel & Begho, 2023).

10. Conclusion

In this review, we critically examined the scientific literature on the environmental impacts of insect farming. The sustainability of insect production is influenced by several factors, including the type of substrates used, production location, scale, insect species, and the specific end-use products they are meant to replace. Our key conclusions are as follows:

1. On paper, insect farming appears to hold potential for contributing positively to a circular economy, particularly due to its ability to process waste and substitute meat. However, in practice, the industry's current trajectory in Western countries does not consistently align with these goals, primarily due to substantial economic and technical challenges. For example, the limited use of waste substrates undermines the environmental case for insect farming.
2. In the food sector, only about 10% of insect-based products aim to replace meat, with the majority substituting plant-based items or being incorporated into products like cookies, snacks, and pasta. While studies are lacking, including insects in these products likely increases their environmental impacts. While insects are more sustainable than conventional livestock in most cases, current data suggests they do not offer significant advantages over plant-based meat substitutes, which tend to have a lower environmental footprint and higher consumer acceptance.
3. For insect-based pet food, which accounts for half of the insect farming market, we found a lack of data, but available evidence indicates a significantly higher carbon footprint compared to conventional products.
4. Additionally, there are concerns about the potential risks to local biodiversity from escaped insects, particularly regarding the spread of pathogens, parasites, and harmful genes.
5. Regarding insects as feed, although results vary, most LCAs indicate that insect farming has a higher climate impact than soybean meal or fishmeal when food waste is not used as a substrate—and, in some studies, even when waste is used. While insect-based feeds could potentially reduce forage fish depletion or, in some cases, land use, their high production costs and scalability issues limit their ability to reduce reliance on conventional feeds in the near term.

Alternative solutions, such as sustainably sourced soy or innovative fish feed formulations, appear to be more promising for reducing the environmental footprint of the food system.

6. The use of insect frass as a fertilizer offers some promising benefits, particularly due to its nutrient content and potential to enhance plant resilience. However, these benefits could be undermined by the need for heat treatment, and there is uncertainty about whether frass will be economically competitive. Some studies also report high greenhouse gas emissions associated with its use in soils.
7. Despite these challenges, some improvements are possible. Certain studies suggest that insect-based products could be environmentally beneficial, but only in cases where production systems are highly efficient (Smetana *et al.*, 2023a). The use of waste is important in this context. Technological advancements, such as heat recovery from nearby industrial processes, could help reduce environmental impacts. Depending on economic viability, insects could play a role in waste management on small scales, especially with local substrates. The industry remains in its infancy, and while the versatility of insects presents potential, predicting which applications will be economically viable and sustainable at scale remains complex.
8. It is worth keeping in mind that there are significant knowledge gaps in the literature. Future research that addresses these gaps—specifically, comprehensive evaluations of insects farmed under industrial-scale conditions for realistic end-use products—would provide a clearer understanding of the prospects for insect farming.
9. Specifically, studies should explore the environmental impacts of insect-based foods that do not replace meat, such as snacks, pasta, and bars, and compare insect-based meat substitutes with alternative proteins. In addition, the environmental impact of insect pet foods should be assessed. More data is required on the risks to local biodiversity and the potential ecological impact of frass following heat treatment. Additional LCAs are needed, with substrates representative of industry conditions.

While specific applications of insect farming show potential, the available evidence suggests that, in most cases, its impact on the sustainability of the food system is less positive than initially promised.

Methods

The studies considered in this literature review were primarily retrieved from searches from Google Scholar, Scopus, OpenAlex and ScienceDirect, between August 2023 and September 2024. Other tools such as SciSpace and Consensus were also used. Combinations of the following keywords were used: “insect farming” (or insect farm[s]”), “environmental impact[s]”, “Life Cycle Assessment” (or LCA), “CO2” (or “global warming”, or “greenhouse gas”). For more completeness, terms like “black soldier fly”, “mealworm”, or “cricket” were also used. All consulted references were in English or in French.

Additional studies were sourced by consulting the references used by reviewed papers or from the prior knowledge of the present paper's authors. Some studies were identified by searching through the work of key authors in the field, such as Arnold van Huis, Sergiy Smetana, Dennis Oonincx, and Imke de Boer. Finally, colleagues working on alternative proteins also provided some resources. The references were prioritised based on their recency, especially those published from 2020 onwards. Given the rapidly evolving nature of insect farming, earlier studies are comparatively less up to date. An effort was made to screen the most regularly referenced pre-2020 studies.

A PRISMA flowchart is shown in Figure 2.

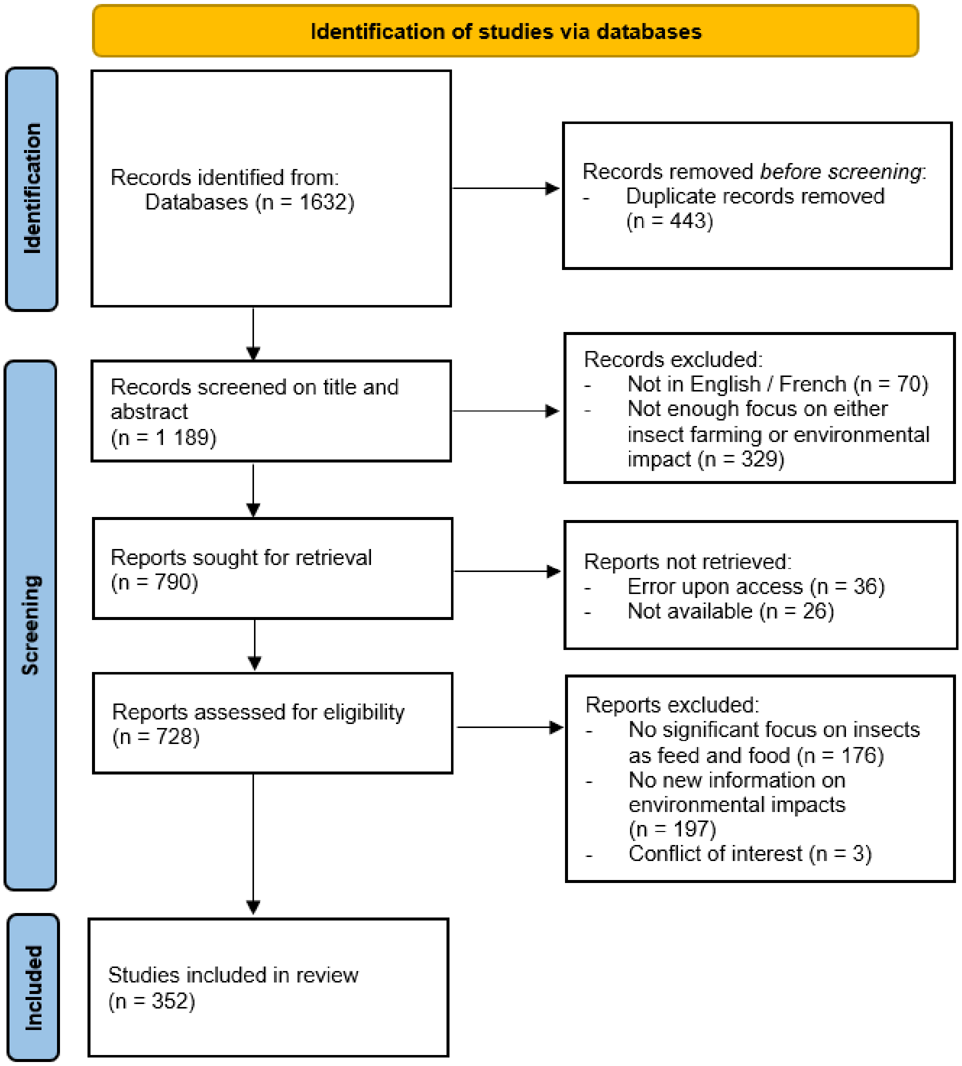

Figure 2. PRISMA 2020 flow diagram (Page *et al.*, 2021)

We focused on insects as food and feed, as well as fertiliser. While peer-reviewed journal articles were prioritised, reports from broader sources, such as non-governmental organisations, were also considered due to the limited availability of certain data, especially on market funding. To avoid conflicts of interest, efforts were made to avoid relying on studies funded by companies from the insect industry.

The combined research found a total of 1189 studies. Following the removal of duplicates, an initial screening was performed on the title and abstract. Following this step:

- 329 papers were excluded due to not having a significant focus on insect farming or its environmental impact. Their focus seemed unlikely to provide new information on the topic.
- 62 papers were excluded as the full text could not be retrieved, such as books suggested by Google Scholar that led to an error page.
- 70 papers were excluded as they were not in English.

Following this, a more advanced screening was performed, examining the content of the paper to assess its relevance to the literature review:

- 176 papers were excluded as their content was focusing mostly on other sectors. While they did mention insect farming, it was briefly, as a potential solution, without delving significantly into its environmental impact besides some basic claims. For instance, this was the case of many papers on waste management or aquaculture feed.
- 197 papers were excluded due to not having enough of a focus on environmental impacts. Their focus was rather on nutritional, economic, or social aspects. Sometimes, they provided claims about the sustainability of the sector, or even a small section, but did not add new data compared to other studies, or specific values such as greenhouse gas emissions obtained in farms. When they cited other studies on the sustainability of the sector, we made sure to screen them for the literature review.
- 3 papers were excluded due to a potential conflict of interest.

The precise criteria for inclusion were the following: (1) studies that performed a LCA with detailed numerical data on the environmental impact of insect farming; (2) studies that provided a review of other

LCAs; (3) studies that provided a detailed section on the environmental impacts of the industry, whether quantitative or not, with new information compared to other papers; (4) reviews comparing the environmental impacts of several products of which insects are part of, e.g. meat substitutes or aquafeed; (5) studies focusing on the broader context with a relevant perspective on the sustainability potential of insect farming, such as studies providing information on social, economic or logistical constraints.

After this comprehensive review, 352 papers were included in the review.

Our analysis focuses on the current state of the insect farming industry, primarily in the Western context, where most large-scale companies are based. While insect farming is common in other portions of the world, it is often performed at a smaller scale, although more companies could focus on these regions in the future, in a different economic, technological and climatic context. We also emphasised studies that reflect current industry practices, such as using high-quality substrates for feeding insects.

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The authors have no conflicts of interest to declare.

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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 analysed in this study.

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