Is turning food waste into insect feed an uphill climb? A review of persistent challenges

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Abstract

A significant challenge within our present food system is the vast quantity of food that is wasted. Insect farming has emerged as a potential solution, providing a means to convert waste into valuable agricultural resources, such as livestock and aquaculture feed. Through a literature review and publicly available data from companies in the sector, we examine the types of materials currently used to raise insects at commercial scales, and analyse whether those materials compete with conventional animal agriculture or other economic sectors. While the idea of turning trash into treasure for insect agriculture may be appealing in theory, the reality appears to be more challenging. Only some species of insects can be farmed using food waste, while others perform poorly. The inconsistent availability and quality of food waste pose significant obstacles to the establishment of large-scale insect farms aimed at consistently yielding high-quality products. Consequently, insect-farming companies often resort to utilising high-quality feeds already in demand by other sectors. Moreover, competition intensifies for the limited pool of food waste suitable for insect agriculture, as various industries, including agriculture, aquaculture, pet food production, and biogas manufacturing, vie for the same resources. Additionally, concerns regarding food safety due to contamination risks constrain the types of food waste viable for insect cultivation. Realising the potential of food waste in insect agriculture necessitates substantial logistical investments, particularly given the decentralised nature of household and municipal waste management systems. Overall, turning food waste into insect feed faces a range of persistent challenges that makes the widespread use of insects in addressing food waste an uphill climb.

Keywords

black soldier fly; circular economy; cricket; frass; food safety; insect farming; waste hierarchy; yellow mealworm

1. Introduction

Food waste is a key issue in our current food system. Approximately one-quarter of the food produced for human consumption is lost or wasted (Poore and Nemecek, 2018; United Nations Environment Programme, 2021). Moreover, according to FAO estimates, the food that is lost and wasted could feed 1.26 billion hungry people every year (FAO, 2019). Consumers in high-income regions generate a large amount of this food waste. In the UK alone, about 15 million tonnes of food are wasted annually, with the majority ending up in landfills, composting, or undergoing anaerobic digestion (Salemdeeb et al., 2017), resulting in a squandering of energy, land use, resources and increased greenhouse gas emissions (FAO, 2013). In 2012, global food waste and food loss was estimated to have an environmental, economic, and social cost of approximately 2.6 trillion USD (FAO, 2014).

Dou et al. (2018) define three major types of food waste: 1) agricultural and manufacturing co-products/byproducts (with typically uniform and known ingredients, e.g. wheat middlings, oilseed meals, distillers' dried grains); 2) residuals and refusals from food preparation and processing (such as those from large-scale bakeries or facilities); and 3) household and catering waste (e.g. from restaurants, cafeterias, hotels) with an unpredictable content, often a mix of plant and animal products. Mixed household waste is particularly relevant as it constitutes nearly 70% of food waste in high-income countries in Europe (United Nations Environment Programme, 2021).

Recent studies have identified various methods to add value to organic waste instead of disposing it in incinerators or landfills. These methods can be conceptualised in a pyramid-shaped food waste hierarchy (Salemdeeb et al., 2017). The food waste hierarchy suggests a prioritisation of different approaches. Reducing food waste is the most crucial step, followed by reusing and redistributing waste (the second step) and recycling waste as compost or animal feed (the third step). Under this framework, feeding waste to animals can help reduce food waste, but only at the third step in the waste hierarchy. The potential impact of this technique will therefore be limited to treating only aspects of food waste that cannot be addressed by the first two stages.

A recently emerging solution that has been proposed to help address food waste is insect agriculture. It has been suggested that insects could contribute to a circular economy by revalorising large quantities of waste and using it to feed humans and animals, thereby reducing environmental impact (Moruzzo et al., 2021; Smetana, 2023). This approach could also lead to cost savings compared to conventional waste disposal methods (Food Standards Agency, 2023; Madau et al., 2020; Pleissner and Smetana, 2020). Insects could help "close the loop" of the food system by reingrating wasted nutrients and transforming them into feed or food as well as usable by-products, such as fertilisers, chitin, antimicrobial peptides or lauric acid (Smetana, 2023). However, assessing the effectiveness of this process and its future impact on the circularity of the food system is still at the design stage (Smetana, 2023). Several studies have shown that certain insect species can be fed a wide range of food waste, yielding promising results (Ites et al., 2020; Salomone et al., 2017; Varelas, 2019; Vauterin et al., 2021). In particular, black soldier fly larvae (BSFL; *Hermetia illucens* L.) and housefly (*Musca domestica* L.) larvae have demonstrated the ability to convert organic waste into nutrient-rich feeds (Čičková et al., 2015; Derler et al., 2021; Spranghers et al., 2017). In contrast, yellow mealworms (*Tenebrio molitor* L.) and house crickets (*Acheta domesticus* L.) have limited potential as they need quality ingredients to thrive (Billen et al., 2020; Lundy and Parrella, 2015; Skrivervik, 2020).

For insect agriculture to successfully contribute to a sustainable food system, the use of insects in treating food waste needs to be environmentally sustainable and economically viable. The environmental impacts of insect farming depend mainly on the type of substrate used for feeding insects (Halloran et al., 2016; Lundy and Parrella, 2015; Oonincx, 2021; Oonincx and de Boer, 2012; Salomone et al., 2017; Smetana et al., 2019; Sogari et al., 2023; Vauterin et al., 2021). Utilising waste as a substrate might lead to reduced environmental impacts and support a circular economy (Moruzzo et al., 2021; Smetana, 2023). However, if waste is not used, insect farming would have a greater environmental footprint and potentially compete with resources suitable for human consumption, animal consumption, and existing industries (Gasco et al., 2023; Thévenot et al., 2018). It has been suggested that using waste as feed for insects is also essential for the economic viability of insect farming (Varelas, 2019). However, it may be profitable if insects are reared on very cheap, low-value waste streams (van Huis, 2022; van Huis and Gasco, 2023).

A crucial factor in the success of insect farming is finding suitable substrates that cannot be fed directly to aquacultured fish or livestock, are free from contaminants, are locally available in large quantities, are logistically easy to handle and store, have a long shelf-life, and are available on the market at a competitive price (Derler et al., 2021; Gasco et al., 2023). In other words, for insect farming to be sustainable, insects need to be able to bioconvert low-value waste into useful nutrients (Gasco et al., 2023). To assess whether this is a plausible scenario, we first need to look at the substrates currently in use.

Through a literature review and publicly available data from companies in the sector, we examine the substrates currently employed by the insect farming industry. Our analysis centres on determining whether these substrates create competition with resources that could be utilised by other industries. Subsequently, we explore the challenges the insect industry faces in adopting waste as feed on a large scale. Overall, we argue that the insect agriculture industry faces a range of persistent challenges that makes the widespread use of insects in addressing food waste an uphill climb.

2. Substrates currently used in the insect farming industry

Examining the substrates currently used by the main insect farming companies can inform us about what insects are likely to be fed in a commercial context in the future. (Table 1). Currently, the industry leaders by production capacity and funding, such as InnovaFeed and Ÿnsect, appear to predominantly utilise grain-based byproducts and coproducts from food manufacturing and bioethanol production, as indicated in public articles and statements. The president of aqua nutrition at Cargill, Helene Ziv-Douki, reports: "We have a big starch presence, both in wheat and corn, and most of these insect factories are using the byproducts of corn and wheat starch to feed the larvae of the flies" (Gibson, 2022). These byproducts can be used as conventional animal feed.

The IPIFF (International Platform of Insects for Food and Feed), which represents the European insect industry, surveyed their members on their substrate usage in 2018 (IPIFF, 2018). Most companies used fruits and vegetables, cereals, agricultural co-products, or even commercial soy-based feed, while only a minority of companies (38%) used waste products such as former foodstuffs. The percentages reported in the survey represent the proportions of IPIFF members making use of the stated substrates, not the actual volumes or proportions in the feed mixtures. Indeed, these findings may likely overstate the use of waste by volume, especially considering the large use of grain-based byproducts/coproducts from industry leaders like InnovaFeed and Ÿnsect which dominate production volumes.

Waste appears to be rarely used as a substrate for insects in a commercial setting and even less at an industrial scale. Skrivervik (2020) corroborates this finding, as none of the insect farms they studied in the Netherlands used food waste as feed (although two out of 13 used coffee grounds, apple pulp, and leftovers from beer production). Companies generally prefer nutritious feeds such as cereal-based co-products because they are available in large and regular volumes, are of consistent quality, perform satisfactorily in terms of insect growth for a greater number of species, present less risk of contamination and, in some cases, are less expensive.

This led Skrivervik (2020) to conclude that although it could positively contribute to the bioeconomy, it is somewhat unlikely that using food waste as insect feed can significantly reduce food waste globally in the current landscape. This might shift in the future with changes in legislation, consumer acceptance, and further research, but currently, this remains a significant challenge. As the use of non-waste substrates like grain byproducts is inconsistent with the sustainability claims of insect products, this might undermine one of the main selling points of insect farming and might lead to reduced demand.

2.1. Competition for high-quality substrates

Many studies point out that from a global perspective it is inefficient to feed insects with materials that could be fed directly to other animals, as in this situation insects would simply add another unnecessary step in the production chain. (Ites et al., 2020; Smetana et al., 2019, 2016). Following this perspective, products that can be a part of the human diet or used as feed for livestock should not be regarded as sustainable substrates with which to feed insects. Yet many of the substrates identified as being regularly used by companies in the insect farming sector could be used for conventional animal feed and, in some cases, for human food. These include fruit and vegetables, cereals, agricultural co-products and commercial feed.

Agricultural co-products, byproducts, and food-processing residuals are already routinely used in animal feed. These products account for nearly 30% of global livestock feed intake (Dou et al., 2018; Food Standards Agency, 2023; McBride et al., 2021; Mottet et al., 2017) and up to 70% in some countries such as the Netherlands (Elferink et al., 2008).

In the United-States, livestock are fed millions of tons of grain-based milling co-products, oilseed meals, and animal proteins annually, as well as brewing and ethanol co-products, like wet distillers grains (Ferguson et al., 2016). 10% of the feed for laying hens was composed of distillers' dried grains with solubles (DDGS) from ethanol production (McBride et al., 2021). This practice is common enough that manufacturing byproducts are not included in food waste estimates (ReFED, 2016).

If insects are fed a diet similar to conventional livestock, they will ultimately add more competition for feed, contributing to an increase in global feed prices (Halloran et al., 2016; Lundy and Parrella, 2015). This could translate to an increase in the cost of animal products (Quang Tran et al., 2022). Assuming that livestock farmers cannot obtain certain types of feed because insects use them, they may then have to buy more commercial grains to compensate, which would increase competition for food and land (Quang Tran et al., 2022). What makes a substrate desirable for insect feed is often what makes it desirable for other uses. (Roffeis et al., 2020). For instance a high-quality substrate, like brewery waste, has a high-efficiency conversion (rich in valuable proteins, dietary fibres and calories) making it a popular feedstuff. For example 70 % of brewer's spent grains are already being used for animal feed (Terefe, 2022). Lower-quality substrates are less in demand but they are also less efficient, which leads to a trade-off (Roffeis et al., 2020, 2017).

Commercial feed, used by a third of insect producers in the 2018 IPFF survey, is a crucial issue since this feed often includes soy. Producing soy requires using arable land, exacerbating the competition for agricultural land. Soy production in some countries is also associated with specific environmental and human rights problems (Schilling-Vacaflor and Gustafsson, 2024). The use of rapeseed meal may also exacerbate competition for agricultural land (Kearns, 2021; Tyler, 2021). The insect farming company Ÿnsect reported that one of their farms was constructed in a wheat- and rapeseed-producing region to keep the company's activity local (Ynsect, 2021).

2.2. Competition for waste with other industries

For insect farming to become a component of a sustainable food system, it is essential for insect producers to focus on materials not already valued by other industries (Gasco et al., 2023; Ites et al., 2020; Quang Tran et al., 2022; Roffeis et al., 2020). However, while using high-quality unused waste streams would be the most favourable, true waste streams are likely to vanish if technological progress enables their reuse within a circular economy (Geissdoerfer et al., 2017; Roffeis et al., 2020).

Various sectors already utilise organic waste, such as biogas production and composting, and insects could compete with them (Thévenot et al., 2018). Due to the circular economy concept, the processing of agricultural waste, by-products, and co-products into fertilisers, materials, or energy, like biodiesel, is gaining attention (Azadbakht et al., 2023; Gontard et al., 2018).

Organic waste is increasingly considered a valuable resource with high agronomic and energy potential, rather than unwanted material (Le Féon et al., 2019). For example, new value chains have been established to utilise organic municipal household waste through processes like anaerobic degradation, which can produce biofuel, electricity, or heat (Liverød, 2019). New sectors can develop rapidly, as has happened for biogas production. Biofuel derived through anaerobic digestion is a crucial element in Norway's efforts to reduce environmental impacts from heavy road transport. Another example comes from West Africa, where the value of organic waste is projected to rise in the future in response to increases in food demand and decreases in food productivity (Hollinger and Staatz, 2015; Palazzo et al., 2016). Redirecting these waste streams towards insect consumption could potentially result in society losing access to resources deemed sustainable (Liverød, 2019). To illustrate, one insect farmer explicitly states that with their new factory, byproducts from a local food production factory can now be "upcycled into feed instead of being sold for biogas" (Aquafeed.com, 2023).

Competing with these value chains might be warranted from an environmental perspective if insects allow a more efficient utilisation of waste resources. While some papers argue that competition with the bioenergy industry might increase environmental impact (Quang Tran et al., 2022; van Zanten et al., 2015), others argue that feeding BSFL on brewery grains or expired food has a better environmental and economic efficiency than incineration and anaerobic digestion (Ites et al., 2020). BSFL meals are also environmentally more efficient and economically comparable to the operating costs of composting (Ites et al., 2020).

Additionally, it is worth noting that businesses are increasingly prioritising food waste prevention—the first step in the food waste hierarchy—which may lead to a reduction in food waste volumes over time (McBride et al., 2021). This means that investments in end-of-pipe infrastructure and waste-to-feed processing must consider the return on investment and the potential reduction in food waste in the long-term. Furthermore, efforts to use surplus food as conventional animal feed have been hindered during the COVID-19 pandemic, as there has been a decrease in food waste generation due to lower operational capacities in retailers, restaurants, hotels, and cafeterias (Food Standards Agency, 2023). Policies that prevent food waste would further reduce the amount of waste available for animal and insect feed.

2.3. Competition for waste with conventional agriculture and pet food manufacturing

Surplus fruits and vegetables, former foods and food leftovers can be repurposed as livestock feed (Castrica et al., 2018; Rajeh et al., 2021). In recent years, there has been a growing focus on utilising food waste as feed for conventional livestock. Research indicates that these materials can be nutritious and safely converted into animal feed using modern technologies (Pinotti et al., 2021; van Huis, 2022). Livestock such as pigs and chickens can be fed with food waste with feed conversion ratios on par with conventional feeds, despite uncertainties depending on the feed source, animal species, age, and length of the feeding trials (Food Standards Agency, 2023; Rajeh et al., 2021; Salemdeeb et al., 2017).

The largest waste stream in the food chain, consumption-stage food waste, poses the greatest challenge but could still contribute to animal feed (Dou et al., 2018). Commercial swine can be fed with food waste collected from restaurants (up to 20 to 50%). Household food wastes can substitute 10% of chicken feed, with comparable feed conversion values (Rajeh et al., 2021). In a survey, 24% of UK smallholder farmers reported feeding uncooked household food waste to their pigs, even despite the current ban on this practice (Gillespie et al., 2015). Many large European and UK retailers, including Tesco, Arla Foods, and Coca-Cola, are investing in waste sorting to repurpose surplus food as animal feed (Food Standards Agency, 2023; WRAP, 2016).

Another avenue is pet food manufacturing, which has been described as the most promising strategy for using food waste as animal feed in the European context (Castrica et al., 2018). Animal co-products already make up a large part of pet food manufacturing (Alexander et al., 2020). Fish and meat surplus, catering waste reflux from households or central kitchens, can be used under specific conditions (Castrica et al., 2018).

Insect farming competes with established uses of waste as feed. The competition for resources in achieving a circular economy means that food leftovers and agricultural co-products might become increasingly expensive (van Huis, 2022). The substrates of greatest interest for insect farms in terms of their nutritional content are also in high demand by conventional forms of animal agriculture. Insect farms may face challenges similar to those faced by other industries in accessing and utilising food waste, and these barriers may be even greater considering the established nature of conventional livestock and anaerobic digestion.

3. Challenges in utilising waste as insect feed

Le Féon (2019) outlines five obstacles to the widespread adoption of food waste as insect feed: 1) Regulatory and societal issues; selling fish or meat from animals that consume waste-fed insects requires regulatory approval to ensure safety. 2) Suitability of organic waste; not all insects are compatible with organic waste as feed, such as mealworms. 3) Competition with other sectors; organic waste is already used by other industries, like biogas production, limiting its availability for insect feed. 4) Waste collection; enhancements in waste collection are necessary to secure a steady supply for insect feed. 5) Variability of organic waste; the composition of organic waste fluctuates across time and space, presenting a challenge for its consistent use as feed. Given these factors and until further research is conducted, it is likely that insect farms will not be able to effectively utilise significant quantities of food waste (Skrivervik, 2020).

Difficulties utilising waste streams have been acknowledged by prominent industry actors. For instance, the CFO of InnovaFeed, Clément Tiret, reported in an interview (Faes, 2022): "The waste is a very interesting topic [...] Although there is some great longer term upside, it is extremely difficult to build an industry with a consistent quality product if your main input has a high level of variability." Tiret also cites the specific case of AgriProtein, a major insect farming company in South Africa that went bankrupt. Before its failure, AgriProtein was a major industry player attracting substantial attention. In 2018, it raised 105 million USD in funding, had an overall value of 200 million USD (CNN, 2018), and was named as one of fifty "genius companies" by Time Magazine (Time, 2018). However, Tiret argues that one of the reasons for Agriprotein's bankruptcy may be the company's attempt to produce at scale on the basis of the complex, variable substrate that is waste (Faes, 2022).

Additionally, agricultural by-products not consumed by humans are often repurposed as animal feed or into non-food products, indicating that lost or wasted parts either lack market value due to regulatory restrictions (for health and sanitary reasons) or are cost-prohibitive to collect and recycle (Elleby et al., 2021). These issues also contribute to the limited use of waste in traditional livestock production.

3.1. Regulatory barriers

The EU and the UK, two major jurisdictions for insect agriculture in the Global North, have regulations that explicitly forbid using food waste that might contain animal products as feed. The use of consumer food waste, slaughterhouse products, manure, and human wastewater or household waste are forbidden. The only waste products and by-products that are allowed are processing waste and former foodstuffs that consist solely of vegetal, dairy, egg, and/or honey origins (Regulation (EU) 2022/1104). The use of most waste products as substrates is also prohibited due to safety concerns about the end products (Mancini et al., 2022). Substrates containing manure or mixed waste materials are also restricted for safety reasons. In the US, the only insects currently approved as animal feed, the BSFL, must be “raised on a feedstock composed exclusively of feed-grade materials” (Association of American Feed Control Officials, 2021) and cannot be reared on non-feed grade substrates such as waste, or fed to non-salmonids (Suryati et al., 2023). As mentioned above, the most relevant type of waste is mixed household waste, which represents 70% of food waste in high-income European countries (United Nations Environment Programme, 2021). However, it is currently not available as insect feed (Lalander and Vinnerås, 2022).

The insect industry is actively working to amend regulations to permit the use of food waste as feed for insects. Certain stakeholders within the industry pinpoint regulatory risks as the primary barriers confronting the sector (Niyonsaba et al., 2023) and occasionally anticipate that legal limitations on utilising waste as rearing substrates will become increasingly restrictive in the future (Niyonsaba et al., 2023).

Regulations are one of the reasons the use of waste as feed has been declining for conventional livestock. For instance, in the US, feeding food waste to pigs has consistently declined (Dou et al., 2018) despite being authorised in several states (Leib et al., 2016). While feeding pigs with food waste was once a common practice in the US, especially near major urban areas (Westendorf et al., 1996), the practice is now limited to a few pig farms. For instance, in New Jersey, the number of swine food waste feeders fell from 250 to 36 between the 1960s and the 1990s (Dou et al., 2018). Similarly, the count of pigs raised on food waste plummeted from 130,000 to under 50,000. This decline is attributed to tighter federal, state, and local regulations. These laws concern not only safety constraints on the use of food waste (e.g. laws requiring cooking waste before processing), but also animal health and transportation. Additionally, the location of feeder farms in relation to residential areas has come under scrutiny, due to concerns that food waste may become a health risk or a nuisance (Brinkley and Vitiello, 2014).

3.2. Contamination risks

Regulations on the use of food waste for animal feed are primarily driven by contamination concerns (Dou et al., 2018; Lalander and Vinnerås, 2022). To illustrate, the UK Food Standards Agency (2023) justifies regulations on food waste as follows: “there is a threat that insects can be disease vectors particularly if reared on waste, and that using insect processed proteins may lead to disease outbreaks. Strict legislation on waste substrates, insect processing, and feeding strategies are needed to minimise feed and food safety risks from insects as vectors of diseases”. Contaminants can enter the body tissue of livestock and fish and impair the animals' health, welfare, and performance (Food Standards Agency, 2023; Schrögel and Wätjen, 2019). The UK Food Standards Agency also stresses the importance of carefully performing the thermal processing of food waste and former foods before their use in animal feed to ensure safety. This calls for the development of safety assessment protocols that employ advanced biotechnologies for early and accurate detection of contaminants (Food Standards Agency, 2023). The Agency adds that the safe adoption of food waste presents a significant challenge for regulatory systems.

Untreated food waste is indeed a common source of infectious bacteria and viruses, as evidenced by the costly foot and mouth disease outbreak in the UK in 2001 that was linked to feeding unprocessed waste to pigs (Rajeh et al., 2021). Annually, this disease imposed economic costs estimated at 6.5 to 21 billion USD (Knight-Jones and Rushton, 2013). Following this event, the UK and the EU implemented a ban on using food waste as feed, significantly limiting its application.

The hazards associated with food-to-food insect production are reviewed in detail by Varelas (2019). Concerning frass, there exists a risk that feeding insects with waste could lead to the presence of pathogenic microorganisms in the resulting frass. (Basri et al., 2022). Some studies identified potential foodborne pathogens in frass, including *Salmonella* spp., Xanthomonadaceae, and *Bacillus cereus* (Kawasaki et al., 2020; Wynants et al., 2019). While high-temperature treatments of frass could potentially eliminate harmful microbes, such treatments could also destroy beneficial microorganisms and biomolecules that enrich soils (Poveda, 2021). Attempts to sanitise the substrate by sterilisation prior to feeding have been shown to reduce the subsequent efficiency of BSFL rearing and may negate the benefits of frass as a fertiliser (Gold et al., 2020).

Certain food wastes may also contain high levels of naturally occurring toxins, like theobromine in chocolate residues, which is harmful in large quantities. Studies have reported that the concentrations of heavy metals and pesticides in food waste often exceed the limits imposed on conventional protein sources (Dou et al., 2018; Food Standards Agency, 2023). Heavy metal contamination is particularly relevant for BSFL (Liverød, 2019). For instance, metals such as cadmium, lead and zinc, when present in BSFL substrate, have been shown to bioaccumulate in BSFL (Diener et al., 2015). The presence of microplastics in food waste is a further concern, as their consumption through contaminated livestock products can lead to human health issues, including genotoxicity, cell apoptosis and inflammation (Food Standards Agency, 2023). It is also essential to determine whether prions pose a risk in a circular insect food production system (Lalander and Vinnerås, 2022). It appears that while prions cannot be expressed in the genomes of insects, insects are nevertheless able to act as vectors if reared on a substrate contaminated with prions (van der Fels-Klerx et al., 2018).

To mitigate these risks, it is necessary to establish standards and certification schemes that define appropriate treatment techniques and waste types suitable for this purpose (Westendorf, 2000). Ensuring the safety and traceability of feed materials for insects is challenging due to a lack of well-documented information regarding the risks associated with rearing insects on different substrates (Liverød, 2019; Skrivervik, 2020). Additionally, there is limited knowledge regarding food safety concerning the use of insects, which may act as a barrier to their introduction in Western countries (Lange and Nakamura, 2021; van der Fels-Klerx et al., 2018).

Therefore, the most viable option is for insect farms to use "hazard-free substrates" (Lange and Nakamura, 2023). For example, while the BSFL can *theoretically* feed on manure, organic waste, animal processing by-products such as offal or blood and human faeces, this may introduce safety risks for both humans and animals in practice (Derler et al., 2021; Liverød, 2019). The general ban on using these waste products as animal feed appears unlikely to change in the near future, as there is a very high evidence bar that must be cleared to confirm the safety of this practice (Derler et al., 2021).

3.3. Species-specific limitations on food waste

The claim that "insects can valorise waste" is often stated broadly. However, this obscures the fact that not all insects can effectively grow or survive on low-quality substrates. Different insect species perform differently. As such, the capacity to utilise organic waste is limited by the type of insect species and type of waste (Le Féon et al., 2019).

The insect species most commonly reared in industrial insect agriculture are crickets, mealworms, and BSFL. One study found that crickets fed minimally processed municipal waste experienced a 99% mortality rate before reaching a harvestable size (Lundy and Parrella, 2015). Information on the use of other waste types is limited, but evidence suggests that crickets are infrequently reared on waste substrates (Skrivervik, 2020).

Mealworms, among the most cultivated insect species for food and feed, are not an ideal candidate for using waste (Le Féon et al., 2019). Some studies note that organic waste and manure hinder growth, likely due to the substrates' low nutrient density and high starch content (Harsányi et al., 2020; Le Féon et al., 2019; Quang Tran et al., 2022). The CFO of Innovafeed states plainly that “the mealworm cannot be fed on organic waste streams” (Faes, 2022). The yellow mealworm can thrive on various other substrates, including dried brewing by-products, potato processing derivatives, biofuel industry by-products, livestock feeds, and plant-based products (van Huis and Oonincx, 2017). They also consume wheat bran, bakery products such as bread and distillers' grains (Derler et al., 2021; Ites et al., 2020). However, as discussed above, these substrates are already being used as feed for conventional livestock. Household waste is generally unsuitable for yellow mealworms, as it is generally quite wet, contrasting with their natural preference for dry substrates. Consequently, attempts by Ites et al. (2020) to grow the yellow mealworm cost-effectively on waste have been unsuccessful, as the waste lacked the necessary solid content, and methods to increase it were neither efficient nor economical.

Additionally, the long development cycles of the yellow mealworm, ranging from 26 to 730 days depending on feed quality, further complicate their use in a continuous, economically productive system (Ghaly and Alkoaik, 2009; Li et al., 2013). The study by Ites et al. (2020) indicates that the development of yellow mealworm larvae took significantly longer periods on certain waste substrates compared to good quality feed. Specifically, larvae took 103 days on dry expired food, 85 days on dry brewery grains, and 168 days on dry potato peels, in contrast to just 26 days on high-quality feed (Li et al., 2013; Oonincx et al., 2015; van Broekhoven et al., 2015). This suggests that rearing yellow mealworms on food waste could pose a substantial threat to the economic viability of the farm.

A longer growth period may also cause a higher environmental impact of the farm in energy and water consumption. This suggests a trade-off between the use of waste and the environmental impact associated with other aspects of the production system. For instance, incorporating distiller's dried grains with solubles into the yellow mealworm diet resulted in a higher overall environmental footprint (Quang Tran et al., 2022). Given the limited range of waste materials suitable for mealworms, it is suggested that conventional livestock feed is the optimal diet for the yellow mealworm (Quang Tran et al., 2022), which would directly compete with traditional livestock feed sources.

Species like the BSFL and the common housefly appear to be more suited to convert low-quality organic waste into protein (Derler et al., 2021; Diener et al., 2011; van Huis and Oonincx, 2017). BSFL can consume a diverse array of wastes, including manure (Newton et al., 2005; Oonincx et al., 2015), rice straw (Manurung et al., 2016), catering waste (Surendra et al., 2016), fish offal (St-Hilaire et al., 2007) or even human faeces (Banks et al., 2014; Lalander et al., 2013). Nevertheless, challenges such as lower survival and growth rates persist. For instance, when compared to a control diet, survival rates of BSFL on various types of manure were lower: 45% on dairy, 78% on poultry, and 73% on swine manures (Miranda et al., 2020). These survival rates can hinder economic viability.

3.4. Challenges associated with waste collection

The use of food waste as animal feed introduces a range of logistical hurdles. Waste treatment involves sophisticated treatment technologies and control and traceability measures (Dou et al., 2018). In the few countries where food waste is extensively utilised for animal feed, waste treatment is centralised and exclusively conducted in registered facilities, primarily because of the requirement for specialised equipment (Shurson, 2020). This centralised approach requires significant infrastructure and logistics and is usually not performed by the companies utilising the waste.

As food waste is geographically dispersed, the collection of this waste incurs significant costs (Ng et al., 2017) due to the need for a comprehensive collection network and quality control at each point of collection (Cobo et al., 2018). This is more complex and expensive than acquiring protein from a concentrated agricultural source (Lalander and Vinnerås, 2022) : if co-products/by-products and residues from food processing are already commonly used as feed, it is mainly due to their concentrated nature, which allows logistical efficiencies, economies of scale and high predictability, both in terms of quantity and quality (Dou et al., 2018).

In comparison municipal and household wastes are characterised by variable quality and high moisture content (Rajeh et al., 2021) and are produced at scattered locations (Ng et al., 2017). Establishing an efficient waste collection system is essential for food waste to be viable as animal feed. Given that such waste typically has a high moisture content (70-80%) and is quick to spoil, it must be used within a short time window and handled correctly (Dou et al., 2018). The costs associated with various steps, such as timely waste collection, maintaining high hygiene standards, thermal treatment, transport, and handling, all contribute to the overall expenses, which are crucial to consider when evaluating feasibility (Food Standards Agency, 2023; Pinotti et al., 2021; Rajeh et al., 2021). Although methods for sorting organic waste are being increasingly advocated, the high expenses related to collection often favour the promotion of smaller-scale strategies like composting or micro-biogas plants, for future development (Le Féon et al., 2019).

For food waste to be appropriate for animal feed, it must not only be fresh but also collected separately from other types of waste to remove unwanted items like plastics and glass that may pose health risks to insects and damage the machinery (Taponen, 2015)Liverød (2019) ; (Taponen, 2015). In Japan, this challenge serves as a rationale for prohibiting the inclusion of household waste in conventional animal feed (Rajeh et al., 2021).

Sorting food waste is a practice that is currently limited to only a few regions (Salemdeeb et al., 2017). In the UK, for instance, the rates of separate food waste collection in 2013 varied greatly, with Wales at 95%, Scotland at 34%, England at 26%, and Northern Ireland at 4% (House of Lords, 2014). Different types of waste have varying properties. Potato peels are abundant and can be used as animal feed (Pal, 2018), but they present logistical hurdles due to their bulkiness and rapid decomposition (Ncobela et al., 2017). These factors, along with nutritional limitations, render them a low-value animal feed (Wu, 2016). When using potato peels for insect feed, Ites et al. (2020) reported that there were difficulties reaching financial viability. Moreover, many by-products need to be processed (e.g. shredding and drying) which may add environmental and production costs to the final product (Derler et al., 2021; Zhang et al., 2019).

Employing locally available by-products is vital for a circular system; however, these by-products encounter limitations due to seasonal and local constraints (Derler et al., 2021). Because of seasonality and inconsistent supplies, storage capabilities may be required, with an added cost (Shurson, 2020). For example, there is more brewer's spent grain during the summer as more beer is consumed. Strategies to counteract this include using other by-products with similar nutrient profiles available during different periods of the year or preserving by-products through drying. However, this last option could also increase environmental and production costs (Derler et al., 2021). Fluctuations in available substrate depending on the season would further complicate the identification of a substrate formula that achieves a suitable growth rate for insects. A former insect company co-founder contends that there may be opportunities for small-scale, localised insect production that allow for the use of waste (Badeski, 2023). However, such opportunities are less viable in terms of large output and economic viability (Badeski, 2023).

Despite the myriad logistical challenges associated with recycling consumption-stage food waste into animal feed on a cost-effective industrial scale, such issues are often overlooked in studies (Rajeh et al., 2021). Instead, research predominantly concentrates on pilot-scale laboratory experiments, with only a few researchers dedicated to addressing specific logistical hurdles. This highlights a notable research gap in the field.

Collecting food waste for feeding to animals, including for traditional livestock, requires considerable infrastructure investment to secure the safety of waste streams. This entails the engagement of all stakeholders within the supply chain, a task that exceeds the capabilities of individual companies alone. Public support is crucial (Salemdeeb et al., 2017), yet research into consumer attitudes towards waste-fed insects is scarce. Le Féon (2019) suggests that even though authorisations might be issued, it is unclear whether consumers in the Global North are prepared to eat meat from insect-fed animals. In China for instance, some studies indicate that safety concerns have negatively impacted market acceptance of food waste in conventional livestock feed, with uncertainties about nutritive values and contamination risks (Chung, 2001), which could ultimately restrict commercialisation (Chen et al., 2015).

3.5. Variability in waste supply

Using food waste as animal feed also necessitates having access to a quality, stable supply of food waste (Salemdeeb et al., 2017). The utilisation of food waste and by-products as animal feed has been very common historically (Westendorf, 2000). However, its prevalence has declined for conventional livestock due to safety concerns and the shift towards commodity grains, which have contributed to enhanced yield and production efficiency (McBride et al., 2021). The adoption of precision feeding, utilising highly nutritious materials like maize and soybeans, has enabled the maximisation of productivity (Banhazi et al., 2012; cited by Dou et al., 2018). For example, while it's feasible to raise beef cattle exclusively on grass, it's common practice to supplement their diet with grain. Cattle finished on grain reach market weight more rapidly than those finished solely on grass, as they receive a higher-energy diet, resulting in more efficient weight gain. In contrast, grass-fed cattle grow more slowly and even produce more greenhouse gases (Capper, 2012; Pelletier et al., 2010).

Likewise, it's reasonable to anticipate that insect-farming companies might prioritise substrates based on criteria beyond mere availability. Insects necessitate feeds suitable for a rapid growth, as productivity and short cycles are required for economic viability and competitiveness. For instance, in Thailand, insect farmers prefer chicken feed because the high protein content enables faster insect growth (Halloran et al., 2016). This results in a system that, from an environmental standpoint, is not necessarily better than poultry production even when insects are consumed as food (Dobermann et al., 2017).

Conversely, utilising waste-derived feed poses a challenge in maintaining consistent quality and availability, cost-effectively and at industrial scales (McBride et al., 2021). The composition and volume of organic waste vary both temporally and spatially (Dou et al., 2018). Inconsistency in waste has proven to be problematic for biogas facilities, which require specific conditions to operate effectively (Le Féon et al., 2019). Since insect growth is sensitive to substrate formulation and characteristics, quality must be maintained even in the face of variable energy content, nutrient content, and digestibility of food waste (Shurson, 2020). Waste type influences the economic and environmental performance of BSFL, which makes insect performance difficult to predict (Gold et al., 2018; Ites et al., 2020). BSFL development time has been shown to vary considerably depending on the substrate used : 10 days on good quality feed, 15 days on brewery grains, 18 days on expired food, 35 days on potato peels (Diener et al., 2011; Ites et al., 2020; Newton et al., 2005; Oonincx et al., 2015; Tschirner and Simon, 2015).

Inconsistencies in quality are particularly problematic when considering the final use of most large-scale insect farms, which produce insect meal used as feed for livestock and aquaculture (Dunn, 2021). Since an insect's nutritional profile is contingent on its diet, achieving consistent values will be a major challenge for the insect sector, as they need to match the nutritional values of conventional feeds (Sogari et al., 2023) while aquaculture and livestock producers require stable and consistent nutritional contents. The same issue arises for the use of frass as a fertiliser, as its effects on soil microbial quality, carbon release, and plant growth vary significantly depending on the substrate used to grow larvae (Gebremikael et al., 2022).

Consequently, producers face a trade-off: high-quality insect feed typically yields a greater environmental footprint but also accelerates growth cycles, whereas lower-quality feed, usually associated with a smaller environmental footprint, may result in longer growth periods and increased resource consumption during the growth phase (Bosch et al., 2019; Smetana et al., 2021, 2016). Certified feed producers manufacture products that meet high standards of safety and consistency, ready for immediate use on farms. This can explain why many insect farms opt for these products (Taponen, 2015).

The use of waste as a substrate suffers from several important knowledge gaps. There is a need for methods to standardise and stabilise feed formulas that incorporate organic waste (Le Féon et al., 2019). Valeras (2019) reviewed initial trials on waste-fed insects that showed promising results, but such trials often omitted critical information such as diet composition, rearing conditions, nutritional value, yield, quality, the specifics of the waste mixtures (proportion, chemical composition, characteristics), and also the cost-efficiency of each rearing method. Additionally, none of the studies presented a technical and economic evaluation. Therefore, the available information is insufficient to develop a standardised insect-rearing method using waste. The inconsistency of household food waste (Lundy and Parrella, 2015) and the lack of data on its nutrient content (Dou et al., 2018) compound the difficulty of creating standardised artificial diets. Instead, Valeras (2019) recommends compiling simpler food industry mixtures of wastes, like spent grain. However, these are commonly used as animal feed, as mentioned above. Research gaps on mealworms in particular include the short duration of feeding trials, the lack of studies utilising pure by-product diets, variability in laboratory conditions, and variability in the choice performance indicators (Derler et al., 2021). There is conflicting literature on the relationship between substrate protein content and insect growth performance. There is also an urgent need for research on cost-effectiveness (Derler et al., 2021).

4. Conclusion

In this review, we examined the types of substrates currently used in commercial-scale insect agriculture, and we explored the barriers preventing the insect industry from adopting food waste on a large scale.

Overall, we find that the insect industry's adoption of food waste as a substrate at commercial scales represents an uphill climb. This is due to a range of persistent challenges. While, in theory, the use of waste as an input for insect farming is promising, particularly in terms of circularity, the irregularity of supply and quality, as well as strong regulatory and logistical hurdles, can make the use of food waste on an industrial scale prohibitively expensive and impractical. Considering these significant challenges, it would be inadvisable to assume that the insect industry will mainly rely on waste streams unsuitable for traditional livestock production. As a result, the contribution of insects to a circular economy in the future might be limited.

Insect producers encounter a significant trade-off, as utilising food waste can potentially compromise the performance of insects and the economic viability of farms. Consequently, in practice, insect farmers often resort to using the same high-quality feeds that are already in high demand by other industries. Moreover, the types of food waste that might be suitable for insect farming are sought after by sectors such as agriculture, pet food, and biogas production. Furthermore, incorporating waste into insect agriculture is impeded by regulatory barriers driven by contamination risks and food safety concerns. To enhance the insect industry's utilisation of food waste, particularly in the context of a variable waste supply from dispersed household and municipal sources, extensive logistical systems on a large scale would be necessary.

Some of these challenges could be addressed by additional, dedicated research. For example, research could focus on developing insect diets that combine food waste with other, more consistent ingredients. This could involve pre-processing food waste to standardise its nutritional content and minimise contaminants. However, it is unclear whether the end result of this research—an insect industry that necessarily uses a large proportion of high-quality feed as substrate and involves resource-intensive pre-processing procedures—would deliver on the promise of insect agriculture as part of a more sustainable food system. Research into large-scale logistical systems specifically designed for collecting and delivering consistent food waste streams to insect farms could also be relevant. Any such logistical system would need to remain cost-effective to be a viable option for a commercial industry. Alternatively, research could contribute to establishing clear standards for the utilisation of food waste in insect production. This could involve collaboration with regulatory bodies to evaluate the risks associated with various types of waste and explore their potential for utilisation in insect farming.

Author contributions

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The authors have no conflicts of interest to declare.

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Tables

Table 1. Substrates used by the major insect farming companies.

Insect company	Substrates
Ÿnsect	Agricultural products such as wheat bran, wheat husk, corn husk and other derivatives of cereals, like rapeseed/canola meal or cake, at its largest farm in France (Gezelius, 2022; Issuu, 2021; Tassan, 2022; Tyler, 2021). Ÿnsect also reports using "more than 300 different feed sources" (Faes, 2022), though these are likely similar in nature to the aforementioned substrates.
InnovaFeed	Corn-based and wheat-based coproducts from processing into starches and sweeteners, including wheat ethanol residues (bran and stillage) (Faes, 2022; Innovafeed, 2023)
Protix	Vegetable residual flows, industrial waste from starch, potato, ethanol and sugar production, plant waste, and by-products from local distilleries, food producers, and vegetable collectors (Foodvalley and FoodHQ, 2020; Jagtap et al., 2021; Mutter, 2022; Protix, n.d.)
Enorm Biofactory	Byproducts from the food industry originally destined to be sold to biogas plants (Aquafeed.com, 2023)
Entosystem	Organic matter in the agri-food industry (Entosystem, n.d.)
HiProMine	Organic waste (New protein, 2022)
Better Origin	Fruit and vegetable waste from retailer Morrisons (in a smaller production model at a local scale) (Mcdougal, 2021)
Agronutris	Agroindustry subproducts and byproducts, possibly including potato peels, wheat solubles, beet pulp, distillers grains and cereals (GlobalPETS, 2021; Remy, 2022)
EnviroFlight	Dried distillers grains with solubles (Jagtap et al., 2021)