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Bioconversion of organic waste by insects – A comprehensive review

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ABSTRACT

The ever-growing human population has forced people to intensify agriculture to meet the demand for food and feed. However, the increase in global agricultural production also means an increase in waste generation, which is mostly improperly managed, especially in low- and middle-income countries where adequate waste management infrastructure is limited and inefficient. Consequently, organic waste has become a global burden due to its negative impact on the environment and human health. In this sense, insect-based bioconversion could be an economically viable, environmentally friendly, and technically feasible approach to organic waste management. Based on this review, organic wastes from agriculture, food industry, household, municipalities, and starch industry are considered as suitable substrates for bioconverter insects. Commonly used insects for bioconversion include the cricket, yellow mealworm, superworm, black soldier fly, house fly, flesh fly and blow fly. Rearing facilities must be adapted to provide the optimal environmental conditions for the growth and development of the reared insect to maximize the bioconversion rate and efficiency. Bioconverter insects and their by-products can be industrially processed into animal feed, fertilizer and biodiesel or extracted to isolate bioactive compounds. The challenges associated with insect-based bioconversion include human and social acceptance, method-, infrastructure- and technology-related problems, the availability of substrates, and political and legal regulations. In summary, insect-based bioconversion of organic waste has the potential to reduce waste, create jobs, provide novel products, and offer a sustainable source of protein to feed the world's growing population.

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1. Introduction

According to the International Feed Industry Federation, the global population is expected to grow to more than 10 billion people by 2050 (Hong et al., 2020; Abd El-Hack et al., 2020). The rapid world population growth, economic development, and urbanization will require significant resources to meet the potentially high demand for food and other agricultural products (Surendra et al., 2020). For example, to feed the rapidly growing world population, the Food and Agriculture Organization (FAO) has projected a 49 % increase in agricultural production and a 64 % increase in egg production by 2050 (FAO, 2017). The estimated increase in consumption by 2050 for pork and poultry will be 105 % and 173 %, respectively (Hong et al., 2020). In addition, the estimated global food fish consumption in 2030 is estimated to be about 17.6 % (30 million tons live weight equivalent) higher than in 2016 (Surendra et al., 2020). It is worth noting that this projected increase in agriculture and food production to meet population growth will eventually lead to water scarcity, deforestation, and shortage of arable land partly due to urbanization and climate change (Ravi et al., 2020; Shahida Anusha Siddiqui et al., 2022). An increase in global agricultural production also means an increase in waste generation. For example, food waste alone accounted for about 100 million tons per year in 2015 and is projected to reach 126 million tons in the European Union in 2020 (Salomone et al., 2017). The cost of solid waste management amounted to around 205.4 billion dollars in 2012 and is expected to rise to around 375.5 billion dollars worldwide by 2025 (Abubakar et al., 2022).

Globally, a significant amount of organic waste is produced and improperly disposed of, particularly in low- and middle-income countries where there is inadequate infrastructure and technical inefficiencies in waste management (Kanhai et al., 2021). The management of organic municipal waste has become a global burden due to its impact on the environment and human health. Organic wastes cause flooding, air pollution, and public health problems (e.g., respiratory diseases, diarrhea, and dengue fever) (Kanhai et al., 2021). In addition, organic waste is the third largest source of carbon dioxide emissions (3.3 billion tons of the greenhouse gas CO₂ equivalent) in the world, which is twice the amount of CO₂ generated by all ground transportation in the United States of America combined (Sarpong et al., 2019).

Current organic waste management strategies included composting, landfilling, open dumping, incineration, conversion to animal feed, and anaerobic digestion (Surendra et al., 2020). However, numerous limitations have been associated with these management strategies (Siddiqui et al., 2022). For example, illegal open dumps and landfills remain preferred methods of organic waste disposal or treatments in most developing countries leading to significant environmental (greenhouse gas emissions, ground- and surface-water pollution), health (disease vectors), economic and social problems (Abubakar et al., 2022; Siddiqui et al., 2022). Landfilling is estimated to contribute to around 8 % of greenhouse gas emissions. In addition, it takes a very long time for the waste to fully decompose with this standard method of waste disposal. Composite treatment and anaerobic digestion are a widely accepted method for treating organic waste (dos Muchangos and Tokai, 2020). However, the process is associated to unpleasant odours. generated during this process are mainly associated with emissions of volatile organic compounds (terpenes, alcohols, ketones, sulphur compounds, and amines), ammonia, and greenhouse gases (Jiang et al., 2023). Although combustion is efficient, it requires highly technical processes and costly instruments to control gas emission residues (Wei et al., 2022).

A economically viable, environmentally friendly, and technically feasible approach to organic waste management is required to ensure environmental, economic, public health, and food safety, especially in a circular economy where there is no waste. Organic waste should not be reduced as it is still a source of many new products. Researchers have proposed insect-based bioconversion as a viable approach to manage

organic waste (Siddiqui et al., 2022; Surendra et al., 2020; van Huis and Oonincx, 2017; Xiao et al., 2018). Insects such as *Acheta domestica*, *Alphitobius diaperinus*, *Gryllosid sigillatus*, *Hermetia illucens*, *Locusta migratoria*, *Musca domestica*, *Schistocerca gregaria*, *Tenebrio molitor*, and *Zophobas morio* have been identified as effective bioconverters of organic waste (Surendra et al., 2020).

Insect-based bioconversion is gradually being used to treat biowaste because it is affordable and environmentally friendly (Mannaa et al., 2024). *Hermetia illucens* is capable of bioconverting a variety of wastes (up to 70 %), including animal carcasses, food waste, fruit and vegetable waste, and human feces (Franco et al., 2022b; Lu et al., 2021; Scala et al., 2020; Scieuzo et al., 2023a), while the remaining must be managed. Nevertheless, an energy study is needed to compare the energy consumption of insect-based bioconversion with conventional waste management techniques. Energy is needed for insect breeding, processing, and transportation. However, insect-based bioconversion also provides suitable by-products such as animal feed, fertilizer, and biodiesel (Chavez, 2021). In contrast, conventional waste management methods (e.g., landfilling and incineration), also require energy for transportation and processing, but they do not generate valuable by-products (Mannaa et al., 2024). According to Mertenat et al. (2019), an insect-based waste treatment plant consumes less energy (electricity and diesel) and emits less harmful gases (CO₂, CH₄, N₂O) compared to composting in open windrows. In terms of environmental sustainability, the use of insects as decomposers of organic waste can be easily implemented as it requires only simple technical methods, consequently positively impacting on environmental sustainability. Cheng et al. (2021) demonstrated that houseflies (*M. domestica*) are positively used to reduce the mass of various organic wastes, including food scraps, restaurant, and market wastes. Several insect species, such as the yellow mealworm, codling moth, and housefly, have been shown to be efficient models for sustainable food waste management (Fowles and Nansen, 2019a). In addition, insects can reduce pathogens and other vermin on decaying materials as a means of organic waste management (Shahida Anusha Siddiqui et al., 2022). In addition to effective bioconversion of organic waste, insects provide an alternative source of agricultural food, feed, biofuel, and fertilizer (Fowles and Nansen, 2019a). Furthermore, the use of insects in organic waste management can also reduce the need for soy-based feed, leading to massive deforestation and contributing to the decline of marine populations. Moreover, this review also highlights the challenges, regulations, and laws of insect-based bioconversion. Insect-based bioconversion of organic waste has the potential to reduce waste, create jobs, provide novel products, and offer a sustainable source of protein to feed the world's growing population.

2. Types of organic waste suitable for bioconversion by insects

Insects, that feed on decaying organic matter, are a practical choice for biorefinery, valorization of waste, treatment of industrial by-products, and bioconversion of agro-industrial residues as they can concentrate nutrients in numerous waste products at low concentrations (Ravi et al., 2020). Proteins, lipids, chitin, and frass are just some of the high-value by-products obtained from insect bioconversion and nutritional upcycling of waste biomass (Bohm et al., 2023; Franco et al., 2022a; Ravi et al., 2020; Triunfo et al., 2022). Insects convert organic waste into new goods according to the principle of the circular economy. This leads to lower costs for waste management lower resource consumption than alternative protein and fat production, and a higher value of insect-derived products (Piercy et al., 2022).

The bioconversion of food waste by insects is an intriguing prospect because it could pave the way to new methods to achieve environmental and economic sustainability in the food industry and ensure the continuous availability of safe and nutritious food for all, as edible insects are recognized as novel nutritious, functional, and safe food alternatives (Ravi et al., 2020; Salomone et al., 2017). Most people believe that urbanization and food production are incompatible. However,

insect-based bioconversion challenges this assumption by enabling the cultivation of food and feed in urban areas with high population densities (Fowles and Nansen, 2019a). For example, the biodegradation of organic waste can currently be achieved through the use of various insect species. Common examples are *H. illucens*, *L. migratoria*, and *T. molitor* (Surendra et al., 2020).

The poorest growth and waste conversion rates were observed in yellow mealworms *T. molitor* on a starch-rich diet, leading researchers to speculate that this diet may be suboptimal for mealworms because it lacks important nutrients (Liu et al., 2020). The mechanism of biodegradation in larvae of the black soldier fly (*H. illucens*), the yellow mealworms (*T. molitor*), and the dark mealworm (*Tenebrio obscurus*) can be influenced by various factors, such as temperature, nutrient composition, and photoperiod (Ribeiro et al., 2018). The nutrient content, development, and food supplementation of these insects can influence their survival, growth rate, and performance. These factors can also influence fertility, egg yield, and quality in broiler chickens (Xiang et al., 2023). Therefore, there is growing interest in researching the of insect waste and the commercial application of converting insect waste into animal feed, biofuels, and other valuable by-products (Fowles and Nansen, 2019a). This shows that insects are necessary for the food web due to their role as herbivores and detritivores/waste eaters. Fig. 1 shows the bioconversion of organic waste with the help of insects. There are many different species of insects, and among them there are groups that are highly specialized in their ability to thrive on different organic substrates and under different environmental conditions.

Organic substrates are known to be an important source of organic material and have many benefits (Cucina et al., 2021). In particular, the European Food Safety Authority (EFSA) considers the following seven different categories of organic substrates: 1) food-producing animals that have been fed with authorized feed; 2) products intended for human consumption that are no longer safe due to variables such as expire date,

manufacturing defects, or poor packaging; 3) by-products from slaughterhouses that are safe for human consumption but are not used in food production; 4) unwanted edibles from restaurants, caterers, and households; 5) animal manure and gut contents; 6) plant organic waste from sources such as gardens and forests; 7) human manure and sewage sludge (Gaięcki et al., 2023). It is possible to produce high-quality insect biomass from low-quality and high-quality organic material (i.e., waste, by-products, and complex feed). The properties of the biomass and the time required to reach the harvesting atate appear to be strongly influenced by the quality and quantity of certain nutrients in the organic substrate, such as ether extract/fats, carbohydrates, and fibers (Pinotti and Ottoboni, 2021).

3. Insect species used for bioconversion

To address the environmental, economic, public health, and food safety issues associated with the increasing consumption of scarce natural resources for food and feed production, which is unsustainable, as well as the generation of large amounts of organic waste, an approach that is more economically viable, environmentally friendly, and technically feasible is needed to improve food and feed production, and organic waste management (van der Wiel et al., 2019). Therefore, insect rearing on organic waste can be a bioconversion method while providing insect biomass and organic fertilizer. It has been suggested that organic waste can be reduced by insect rearing on various waste products, including agricultural and food waste, household waste, and industrial waste (Varelas, 2019).

Insects used as bioconverters for organic waste can also be fed to pets and animals, especially fish and chickens (Cappellozza et al., 2019; Gasco et al., 2020). Many insect species can convert low-value organic waste, garbage, and organic bases into a protein rich- diet that can replace expensive calf feed such as fishmeal (Lalander et al., 2019).

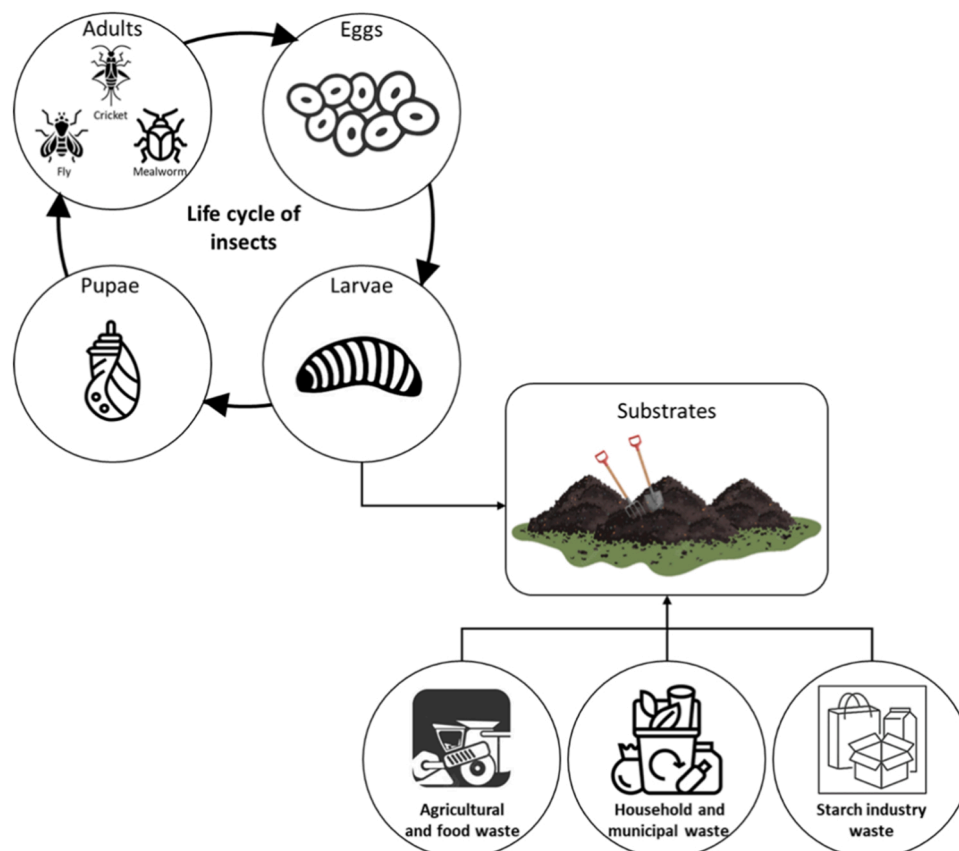


Fig. 1. Type of organic waste for insect-based bioconversion.

Studies on the growth performance and feed conversion of some insect species, indicate that they are sufficient to fully utilize the wide variety of different organic wastes accessible for bioconversion (Fowles and Nansen, 2019b) (see Table 1 for an extended list). It has been proposed, for example, that insects could be a better source of food and/or feed in the long term due to their high food conversion ratio in relation to body mass. Depending on the insect species, developmental stage, and rearing conditions, the effects of light, CO₂, organic matter, and minerals on an insect's performance, physical defenses, body mass, growth, feeding rate, and efficiency can vary. For example, the circadian rhythm, behavior, and metabolism of insects, can be influenced by light and CO₂, while their diet composition and bioavailability can be influenced by organic matter and minerals (Dobermann et al., 2017). Yellow mealworms and crickets are not as effective as Argentine cockroaches and black soldier flies (BSF) as a food source. Moreover, with the proper nutrition, they could utilize their food in a way comparable to that of chickens, considering how much food was actually consumed (Harsányi et al., 2020). With proper nutrition, the studied species can be considered effective farm animals. In addition, the BSF, the most used bioconverter, has a well-documented potential to decompose waste (Norgren et al., 2020). The larvae of generalist saprophytic fly species such as the black soldier fly and house fly are particularly relevant for

use as livestock feed. The larval stages of these species have the potential to convert inedible organic material of low value into profitable biomass, providing an additional opportunity to save some of the 1.3 billion tons of food lost each year (Gold et al., 2018).

“Bioconversion efficiency” refers to the proportion of available nutrients in the substrate that is integrated into the larval biomass (Bosch et al., 2020). If the conversion efficiency of a system is high, it has a better chance of being sustainable in the long term (Parodi et al., 2020). For instance, studies on black soldier fly larvae in recent decades have mainly reported on the efficiency of bioconversion of dry matter, carbon, and nitrogen while growing on various organic substrates. These substrates include animal composts (Beskin et al., 2018; Xiao et al., 2018), vegetable waste (Parra Paz et al., 2015; Sprangers et al., 2017), and sewage sludge (Lalander et al., 2019).

Although insects can biodegrade organic waste, studies have shown that the black soldier fly, BSF, is only moderately suitable for the biodegradation of nutrient-poor fruit and vegetable pulp (Smetana et al., 2019). Similarly, studies have shown striking differences in development rates and feeding efficiency in three species of mealworms when fed one of four different organic waste diets with varying carbohydrate and protein content (van Broekhoven et al., 2015). For this reason, we have highlighted the insect species used in the bioconversion of organic

Table 1

Research studies presenting the utilization of insects in the conversion of organic wastes.

Insect species	Organic waste/substrate	Biological performance	Bioconversion efficiency	References
<i>Hermetia illucens</i>	Animal manure	Larvae growth fed with animal manure peaked on days six and seven, with a weight range of 150–170 mg.	Percent prepupation 45 % (dairy), swine (73 %), poultry (78 %).	(Miranda et al., 2020)
<i>Hermetia illucens</i>	Wheat bran, pumpkin, apple, grape pomace, red onion, red cabbage, and spinach	Poorer and slower development performances were seen in larvae older than 100 days when fed an apple diet, whereas mortality rates were higher for those fed grape pomace and spinach.	The bioconversion findings of larvae fed pumpkin, red cabbage, and red onion were favourable, with values between 14.4 and 25 for the efficiency of conversion of digested material.	(Ribeiro et al., 2022)
<i>Musca domestica</i> and <i>Sarcophaga dux</i>	Chicken, goat and cow manures	Cow manures and chicken manures contributed the highest growth	<i>M. domestica</i> reduced 59.9 ± 4 % chicken manures while <i>S. dux</i> reduced 25.0 ± 1.8 % goat manures	(Abu Hasan and Leong, 2018)
<i>Drosophila suzukii</i>	Coconut fiber, corncob powder, Brewer's and Torula yeast	Yield of number pupae: i) Coconut fiber + Brewer's yeast: 12.59 per g diet ii) Coconut fiber + Torula yeast: 12.36 per g diet iii) Corncob + Brewer's yeast: 10.99 per g diet iv) Corncob + Torula yeast: 6.33 per g diet	Bioconversion had a maximum value of 6 %, but the frequencies with greater dominance were 1 and 3 %. Only coconut-fiber diets bioconverted 3 %.	(Aceituno-Medina et al., 2020)
<i>Tenebrio molitor</i>	Pure wheat bran, mixed-fermented feed and fresh inedible plant biomass	The ratio of growth rates of larvae reared outside to those reared within the closed system rose exponentially over time, reflecting the disparities in growth rates of larvae reared in an open and closed environment.	The overall bioconversion rate was 8.13 %, while 78.43 % of the feed was expelled as frass.	(Li et al., 2015)
<i>Acheta domesticus</i>	Brewery's waste (MD), fruit and vegetables (FV), by-product from wine production (GM), laying hen diet (HF), brewery's spent grains (BG), and trub (TRUB)	Final cricket weight (mean individual weight) ranged between a minimum of 0.0018 g on GM to a maximum of 0.387 g reached on GM+HF.	A maximum value of conversion of efficiency 0.66±0.99 was observed on HF. Only cricket reared on MD showed similar results to the HF, while on all other substrates, the conversion efficiency was lower due to the high mortality.	(Jucker et al., 2022)
<i>Hermetia illucens</i> L.	Restaurant wastewater	24.34 % grease yield and 7.52 L biogas were obtained from corncob	27.34 % of cellulose, 45.14 % of hemicellulose, and 29.33 % of lignin	(Li et al., 2018)
<i>Hermetia illucens</i>	food waste	1 kg of protein by dried larvae caused a GWP impact of 2.1 kg CO ₂ eq, an EU of 15.1 MJ and an LU of 0.05 m ² a	9.4 % (3.1 kg CO ₂ eq), 19.1 % (50.9 MJ) and 22.8 % (0.195 m ² a)	(Salomone et al., 2017)
<i>Hermetia illucens</i>	Olive oil	larval average individual weight increased in all the treatments	bioconversion values ranged from 5.04 % to 6.50 %, decreasing as the replacement level increased.	(Olga et al., 2023)
<i>Hermetia illucens</i>	Chicken feed, pig manure wet, organic municipal household waste, slaughter waste, fast food waste, mushroom stems, and pig manure solid	highest values for dry matter (41.5 %), final weight (137.8 mg), WRI (7.9 g/d), ECI (0.4) and total fat (39.0 %)	DM conversion (25.2 %), CP conversion (54.5 %) and fat conversion (36.2 %)	(Naser et al., 2023)
<i>Hermetia illucens</i>	By-products of apples and mandarins	BSF larvae decomposed apple pomace by 48.0 % and mandarin waste by 61.5 %	Bioconversion efficiency rates of BSF larvae fed with apple pomace were 9.1 % and mandarin waste were 12.1 %	(Koo et al., 2023)

waste in Table 1.

3.1. House cricket (*Acheta domestica*)

Due to their excellent food utilization crickets have become one of the most widely produced insects (Pilco-Romero et al., 2023). However, their metabolic rate and nutritional composition change depending on the environmental situation, and the risk profile should consider the whole production cycle of edible crickets, i.e. storage, transportation, and processing, as well as potential hazards such as disease risks, mycotoxin-producing fungi, and heavy metals (Fernandez-Cassi et al., 2018). During the intensive growth phase of their life cycle, crickets consume protein-rich food consisting of vegetable waste, garden waste, cattle manure, or horse manure at room temperature (Ooninx et al., 2015). The nutrient composition of crickets is altered by the substrate used for rearing crickets, and the low-quality substrates were rather detrimental to cricket growth. Cricket larvae fed with low-nutrient diets had low protein and high-fat concentrations (Pilco-Romero et al., 2023).

In urban entomology, house crickets are also categorized as a nuisance pest due to their loud chirping and ability to cause material damage. But they can also be used to create resilient and circular food systems by serving as a consistent source of protein for both human and animal use (Kumar et al., 2023). Agro-industrial byproducts can be given to many species of highly renowned insects with positive results (Kee et al., 2023). The usefulness of different vegetable byproducts as a substrate for house cricket culture, considering factors such as feed conversion index, biomass output, growth rate, and feeding preferences of the species. Moreover, the feeding substrate may have an impact on the meal's nutritional value by influencing the cricket's proximate composition (Jucker et al., 2022).

Unfortunately, *A. domestica* is not suitable for bioconverting all types of biowaste. According to research by Quek et al. (Quek et al., 2020), crickets fed a diet of *Brassica rapa* (*B. rapa*) and okara did not develop and endure, as well as those fed a diet of *B. rapa* and dog food. Furthermore, the scientists were unable to find any evidence that crickets raised on a diet consisting of both *B. rapa* and okara fared any better in terms of growth or survival than those raised on either diet alone. This study found that while breeding *A. domestica* crickets, okara is only occasionally an acceptable replacement for premium animal feed (Quek et al., 2020). Furthermore, eating carrots had no effect on the crickets' capacity to withstand, grow, acquire weight, or convert feed into useful energy, according to Veenenbos and Ooninx (Veenenbos and Ooninx, 2017). The results show that adding carrots to a regular dry feed and water does not have an impact on the general health, lifespan, weight increase, or feed conversion efficiency of house crickets (Veenenbos and Ooninx, 2017).

3.2. Yellow mealworm (*Tenebrio molitor*)

Many scientists have investigated yellow mealworms, the first insect to be recognized as a new cuisine by the European Commission. While researchers and industry professionals are refining the production process to suit the growing demand for alternative and sustainable protein foods, such as yellow mealworms, mass production is still not cost-effective when compared to traditional protein production. Using food scraps and leftovers as feed for yellow mealworms can help to cut production costs and have a lower environmental impact (Sangiorgio, 2022). In addition, yellow mealworms have a high feed conversion rate and are among the most extensively produced insects (Ge et al., 2023). However, the rate at which their metabolism works, and the nutritional composition of their bodies shift in response to the conditions in which they find themselves (Kröncke and Benning, 2023).

Yellow mealworm larvae fed 13 agro-industrial by-product diets were tested for bioconversion. Rapeseed meal and chicken feed significantly improved larvae feed conversion and efficiency, making them the best insect-rearing combinations (Bordiean et al., 2022). Larval

weight/size and substrate affected nutrient/amino acid levels. Larvae were evaluated as a potential feed for broilers. The 126-gram commercial chicks that were seven days old and part of the experiment were randomly split into nine groups of six broilers each. Yellow mealworm larvae were fed a mixed diet of sorghum protein and soybeans at three different concentrations to analyze feed intake, weight increase, and feed efficiency. These 15-day findings were comparable to those previously reported (Ramos-Elorduy et al., 2002). For example, yellow mealworms and other insects transform a wide range of organic wastes and by-products into nutrient-dense feedstuffs that may be fed back into the production cycle. However, legal and behavioral restrictions have slowed the widespread adoption of this insect, despite its versatility and potential as a substitute source of nutrition and other critical components (Moruzzo et al., 2021).

3.3. Superworm (*Zophobas morio*)

Z. morio, also known as the superworm, is one of the most widely produced insects. This was primarily because of the excellent feed conversion efficiency of these worms. Superworms are viable waste management agent (Rumbos and Athanassiou, 2021). *Z. morio* *Z. morio* are classified as omnivores because they can independently recombine fodder mass and produce all essential amino acids. All necessary amino acids, except methionine, are present in reasonably high concentrations in the amino acid profile of *Z. morio* larvae (Rumbos and Athanassiou, 2021). It is possible to determine the nutritional value of *Z. morio* larvae and their potential as a source of nutrients for both human and animal diets by identifying specific amino acids and their metabolic pathway (Rumbos and Athanassiou, 2021). In addition, they can consume depleted homogeneous fodder substances without any restrictions on the amount of time they spend doing so. The symbiotic relationship between *Z. morio* and nitrogen-fixing bacteria is responsible for their various capacities (Rumbos and Athanassiou, 2021). By measuring the ability of these bacteria to fix atmospheric nitrogen and to collaborate symbiotically with leguminous plants, it is possible to determine the symbiotic effectiveness of various strains of these bacteria on agricultural products (Saranraj et al., 2023). As a result, *Z. morio* larvae were capable of bioconversion. *Z. morio* larvae grow and develop rapidly, requiring more cells for tissue growth and differentiation. As a result, their cell count is larger than that of adults (Saranraj et al., 2023). Changes in cell numbers between larvae and adults can affect their nutritional needs, metabolic processes, susceptibility to infections, and other factors (Yan et al., 2021). Because of this, it is crucial to consider *Z. morio*'s developmental stage while assessing its nutritional content and potential as a sustainable supply of protein (Rumbos and Athanassiou, 2021). The relationship between the type of fodder consumed and the rate at which *Z. morio* grows and adds mass is a topic of the utmost importance in scientific and applied communities (Ashotovich et al., 2018).

3.4. Black soldier fly (*Hermetia illucens*)

Hermetia illucens, commonly known as the black soldier fly (BSF), is a widely distributed species, particularly in tropical regions. It is a widespread fly in tropical areas known as the black soldier fly (BSF). Because adult flies cannot bite or eat, they are not regarded as pathogens because they cannot transmit disease to humans (da Silva and Hesselberg, 2020). Because their larvae feed on dead organic matter, the larval stage is a natural supply of protein for animals to consume (Bonelli et al., 2019). The use of black soldier fly larvae (BSFL) as a treatment for organic waste is becoming increasingly popular in various regions of the world (Ee et al., 2022). As a by-product of waste minimization, it can contribute to the growth of the surrounding area, generate employment opportunities, and dispose of organic waste in the immediate vicinity (da Silva and Hesselberg, 2020). In addition, the production of insect biomass for food and feed, the selling of byproducts, and the operation of

bioconversion machinery are all possible employment opportunities resulting from insect-based bioconversion (Fowles and Nansen, 2019a). As agricultural land becomes scarce, minimizing land use for feed and energy production may become more important than global warming potential and energy use. Insects are a low-land-use raw material for biodiesel (Salomone et al., 2017).

BSFL development was dramatically slowed when fed fermented maize straw instead of the control feedstuff (wheat bran). The number of years spent as an adult and a female's ability to reproduce drastically reduced. Among the nutritional breakdown of the dried BSF larvae, 41.76 % was made up of crude protein, 30.5 % of natural fiber, and 8.24 % of crude ash. When comparing BSFL-fed larvae to those fed a control diet, it was found that the BSFL grease included a greater concentration of monounsaturated and polyunsaturated fatty acids and a lower percentage of saturated fatty acids (Koutsos et al., 2022). The crude protein, crude fat, and nitrogen-free extract content of the leftover maize straw were drastically altered after being bioconverted by BSFL (Gao et al., 2019). In addition, black soldier flies' larvae have been subjected to proteomic and lipidomic studies to assess their potential and applications. The proteomic and lipidomic profiles of these insects can be affected by diverse biological parameters, such as developmental stage, nutrition, and processing technique (Rabani et al., 2019). Insights into the influence of biological factors on this insect's nutritional and metabolic characteristics, as well as their potential as sustainable sources of protein for human consumption, can be gained by comparing the proteome and lipidomic of *H. illucens* larvae (Rabani et al., 2019).

A large-scale study examined the life-history effects of feeding BSFL seven kg of manure (swine, dairy, or chicken) with a control diet. Larvae fed dairy dung took two days longer to reach preparation and had a lower survival rate (45 %) than those fed poultry or swine manure (>70 %). Those fed swine dung reached their maximum weight by day six, whereas the others only began on day seven (Miranda et al., 2020). In addition, a grasp of the load capacity is essential for developing and using this process on an industrial scale. Within this more extensive study, the current experiment aimed to determine how the presence of larvae and the rate at which they fed affected the biodegrading organic solid waste process. It was discovered that both parameters had considerable effects on the bioconversion, with the density of the larvae having the most bearing on the process (Parra Paz et al., 2015).

3.5. House fly (*Musca domestica*)

Musca domestica, also known as the house fly, is a worldwide species that travels with humans and animals from the tropics to the arctic (Geden et al., 2021). The house fly's status as a pest is its primary drawback. Parasites and other infections are just one of the many things linked to this pest (Čičková et al., 2015). House fly larvae were utilized as the carriers in a bioconversion with food waste to obtain valuable maggot protein, oil, and organic fertilizers because of the rising global volume of food waste (Cheng et al., 2021). After undergoing the transesterification reaction with methanol, the maggot biodiesel yielded 87.71 % (Niu et al., 2017). In addition, the housefly significantly reduced the amount of chicken dung by 59.94 % (Abu Hasan and Leong, 2018), and the larvae products of houseflies that converted food waste are acceptable for use in the manufacturing of fish feed (Cheng et al., 2021).

3.6. Flesh fly (*Sarcophaga dux*)

The flesh flies *Sarcophaga dux* is a recognized voracious feeder and could be employed to transform manures into a residue that does not contribute to pollution. Pollen can be an oviposition stimulant (Pastor, 2015). However, the most common substrate utilized to induce oviposition in the family Sarcophagidae is fish, pork, beef liver, or blood. Similarly, the voracious feeding habits of *S. dux* suggest they could be used to recycle manure into a product that does not contribute to

pollution (Abu Hasan and Leong, 2018).

3.7. Blow fly (*Chrysoma putoria* and *Lucilia sericata*)

Blowfly larvae have the potential to reduce the amount of organic waste and produce a protein that can be used in animal feed and biofuel. However, the development of blowflies on various types of garbage may influence their growth rate and body composition, which the fly species and the stocking rate may impact (Niederegger et al., 2013). *Chrysoma putoria* is versatile and efficient in reducing the substrate on various waste products (Parry et al., 2017). *Lucilia sericata* larvae effectively lowered the mass of waste produced by poultry and fish by 2.5 and 5.5 times (Yehuda et al., 2011). The bioconversion rate ranged from 16.6 % to 39.6 %, and the average yield of larvae raised on waste from fish and poultry was roughly 304 g. Between sixty and seventy-seven percent of the total body mass of the larvae and pupae was composed of water and undigested waste (Yehuda et al., 2011). At the same time, the three most significant components were protein, fat, and carbohydrates in that order (Yehuda et al., 2011).

4. Maximizing the insect-based bioconversion through conditioning the rearing system

The sustainability of waste management is a big question with the food industries due to inadequate environmental resources for food production and food loss and waste issues. Breeding insects and their gut microbes to produce tailored insect lineages for the bioconversion of specific waste streams is possible. Complex community interactions in nature drive natural selection, and the spatiotemporal dynamics of the given environment support these interactions (Fowles and Nansen, 2019b). As a result, the "artificial selection" of insects is defined as the intentional anthropogenic control and manipulation of selection forces to promote a specific evolutionary outcome, such as optimizing an insect population to serve as a bio converter of a specific organic waste product (Fowles and Nansen, 2019a; Meyer et al., 2012). Only a few insect species, namely domesticated honeybees (*Apis mellifera*), flightless mulberry silkworm (*Bombyx mori*), and resinous lac bug, are thought to be the result of artificial selection (*Kerria lacca*) (Melillo, 2014).

Currently, only a few insect species are used as bioconverter, like BSF, houseflies, yellow mealworms, blow flies, superworms, and house crickets (Cheng et al., 2021; Gnepe et al., 2012; Harsányi et al., 2020; S. Liu et al., 2018; Parry et al., 2017). Only *H. illucens* and *M. domestica* are only two insect species mostly used for bioconversion due to their sustainability in various rearing conditions, high bioconversion efficiency and maximize yield production. Table 2 lists some of the insects employed in bioconversion, along with the processes and results.

Conditioning the rearing system is critical for providing dependable, affordable sources of high-quality insects for numerous essential purposes, and facilities designed and built to contain and maintain insects under specific conditions. In established insect-rearing systems, problems occur because failure to pay attention to procedural details or a lack of environmental control. Advances in insect rearing have focused primarily on culturing new species, maintaining existing colonies more efficiently, supporting advances in research and pest management, and increasing the use of insects in people's lives. Food, environmental factors (temperature, humidity, or water in the case of aquatic insects-lighting, gas exchange, and soil-for soil-inhabiting insects), containment, etc., are all considered in designing and conditioning a rearing system (Cohen, 2018).

Fig. 2 shows the bioconversion process and several conditioning parameters affecting the insect-rearing system. After the feed has been processed, food waste with an ideal moisture content can be used for bioconversion.

Insect growth and development systems are highly delicate because of several factors, including temperature, humidity, substrate type and concentration, and type and duration of light, among others. Depending

Table 2
Finding of previous studies of insect-based bioconversion including methods for improved bioconversion and organic waste used for the study.

Insect Species	Tactics Used for Optimum Bioconversion	Organic Waste	Main Findings	References
<i>Ephestia kuehniella</i>	A total of 26 combinations of agro-industrial by-products were used as substrate for rearing. Cultures were maintained in a climatic chamber at $25 \pm 1^\circ\text{C}$, $70 \pm 10\%$ RH, and with a photoperiod of 16:8 (L:D).	Agro-industrial by-products (apricots, brewer's spent grains, brewer's spent yeast, feed mill by-products including broken cereal grains, and hatchery waste including eggshell debris, fluff, infertile eggs, dead embryos, and egg fluids)	<i>E. kuehniella</i> larvae survived in four of the ten combinations that were tested. However, in two of these combinations - dried apricots and feed mill by-products - most of the larvae perished before they reached the pupal stage. Brewer's leftover yeast and feed mill by-products were the best combination for bioconversion, and the maximum number of insects matured on this diet.	(Riudavets et al., 2020)
<i>Hermetia illucens</i>	A standard diet (broll) and three organic wastes (brewer's waste, pig manure, and semi-digested grass) were used to maintain an insect colony, which was then transferred to a glass jar. For optimal larval development, the moisture content of the diet was kept between 70 % and 90 %.	Brewer's waste, the solid phase of pig manure, semi-digested grass	The crude protein and fat content of prepupae fed the standard diet and brewer's wastes were significantly higher than prepupae fed pig manure and semi-digested grass. Larvae reduced significantly more dry matter from the standard diet and brewer's waste than the other two diets. Brewer's waste was the most suitable candidate for larvae processing and semi-digested grass was found to be the most unsuitable one.	(Liu et al., 2018)
<i>Hermetia illucens</i>	Corn cob was partially degraded to lignocelluloses and biochemical properties were improved after soaking in wastewater. Anaerobic fermentation.	Corn cob soaked with restaurant wastewater	The highest product rates of glucose, xylose, and arabinose from lignocellulose were obtained at the optimal corn cob soaking conditions of 75°C , 5 h, and 60 g/L. 24.34 % grease yield was extracted after soaking the corn cob for ten days with larvae. Corn cob soaking supernatant (about 500 mL) was used for biogas production by mixing with 30 % anaerobic sludge to produce about 7.52 L biogas with about 3.22 L methane.	(Li et al., 2018)
<i>Hermetia illucens</i>	Nine different nitrogen (N) sources (i.e., NH_4Cl , NaNO_3 , urea, uric acid, Gly, L-Glu, L-Glu: L-Asp (1:1, w/w), soybean flour, and fish meal) were used to optimized bioconversion. Modification of C/N was a key parameter for bioconversion efficiency.	Food waste (Cooked food leftover)	The C/N ratio of 18:1–14:1 was optimal for high waste reduction performance (73.5–84.8 %, $p = 0.001$) and high larvae yield (25.3–26.6 %, $p = 0.015$). A C/N ratio of 18:1–16:1 was also found to be optimal for efficient larval protein yield (10.1–11.1 %, $p = 0.003$) and lipid yield (7.6–8.1 %, $p = 0.002$).	(Lu et al., 2021)
<i>Hermetia illucens</i>	Rearing on a pure okara diet achieved an 85 % waste reduction to yield frass. To cultivate lettuce, the frass was then mixed with soil in a concentration of 10, 20, and 30 % (v/v)	Okara diet	Larval frass was also discovered to be capable of providing sufficient nutrients for lettuce growth as a fertilizer and as a soil amendment.	(Chiam et al., 2021)
<i>Hermetia illucens</i>	The experiments were carried out in a greenhouse at $28 \pm 2^\circ\text{C}$ and 70 % humidity. Suitable mixing of soybean curd residue and kitchen waste for co-digestion.	Soybean curd residue and kitchen waste	Co-digestion (30 % SCR with 70 % kitchen waste) was discovered to significantly increase larval yield, bioconversion rate, and lipid bioaccumulation. Survival rate (98.75 %), prepupal rate (88.61 %), larval biomass (30.32 g fresh and 11.38 g dry mass), bioconversion rate (18.45 %), efficiency conversion of ingested food (28.30 %), and feed conversion ratio (2.51 %) were the appropriate performance parameters of BSF.	(Li et al., 2022)
<i>Hermetia illucens</i>	Dairy manure and chicken manure were mixed at a 2:3 ratio with cellulose-degrading bacteria <i>Paenibacillus polymyxa</i> strain and <i>Bacillus</i> strains for improved bioconversion.	Dairy manure and chicken manure	Survival rate (99.1 %), development time (19.0 d), manure reduction rate (48.7 %), bioconversion rate (10.8 %), food conversion ratio (4.5), the efficiency of conversion of ingestion (22.3 %), cellulose (72.9 %), hemicellulose (68.5 %), lignin (32.8 %), and nutrient utilisation (71.2 % protein and 67.8 % fat.) are the best outcome measures for larvae with <i>Bacillus</i> strain MRO ₂ .	(Rehman et al., 2019)
<i>Hermetia illucens</i>	Rapid valorisation of solid organic wastes for maximum yields.	Coconut endosperm, and soybean curd residue	The protein content of larval feed substrates could be increased by increasing the proportion of soybean curd protein to the coconut endosperm. The highest larval total weight gained, and growth rate was obtained at a coconut endosperm: Soybean curd residue ratio of 3:2.	(Lim et al., 2019)
<i>Hermetia illucens</i>	Rice straw with chicken meat and bone meal at 0 %, 1 %, and 3 % were used for greater bioconversion.	Meat and bone meal	Rice straw inclusion in chicken meat and bone contributed to BSF gut health, stimulating gut microbe-mediated substance transformation or	(Wu et al., 2022)

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Table 2 (continued)

Insect Species	Tactics Used for Optimum Bioconversion	Organic Waste	Main Findings	References
<i>Hermetia illucens</i>	Co-conversion was done for soybean curd residue with pre-treatment of <i>Lactobacillus buchneri</i> followed by <i>H. illucens</i> for co-conversion efficacy, nutrient composition, safety, and anti-nutritional factor concentrations.	Soybean curd residue	decomposition and promoting microbial diversity in frass. Soybean curd residue fed <i>H. illucens</i> and <i>L. buchneri</i> had significantly higher dry mass reduction ($55.7 \pm 0.9\%$), bioconversion rate ($6.9 \pm 0.3\%$), crude protein content ($55.3 \pm 0.6\%$), and fat content ($30.0 \pm 0.6\%$) than soybean curd residue ($49.0 \pm 0.7\%$, $5.0 \pm 0.3\%$, $52.8 \pm 0.3\%$, and $26.1 \pm 0.8\%$, respectively) and artificial feed ($43.9 \pm 0.8\%$, $3.9 \pm 0.1\%$, $50.3 \pm 0.4\%$, and $24.3 \pm 0.4\%$). With increasing CS-BC dosage, larva wet weight advanced by 2–3 days, and the SD reduction rate increased from 72.09 % to 85.37 %.	(Somroo et al., 2019)
<i>Hermetia illucens</i>	Corn straw biochar (CS-BC) at 0 %, 2 %, 5 %, and 8 % was used with soybean dregs for bioconversion for ten days with Black soldier fly.	Soybean dregs (SD)	SD in combination with 2 %, 5 %, and 8 % CS-BC reduced ammonia (NH ₃) emissions by 2.7 %, 3.6 %, and 18.0 %, respectively. Nitrous oxide (N ₂ O) emissions were reduced by 23.6 %, 29.1 %, and 49.2 %, respectively, with 2 %, 5 %, and 8 % CS-BC additions.	(Qin et al., 2022)
<i>Hermetia illucens</i>	Bioconversion is being used to investigate the properties of dissolved organic matter (DOM) and the responses of bacterial community succession in residue during secondary composting.	Food waste	During secondary composting, total nitrogen and ammonium nitrogen concentrations decreased by 11.8 % and 22.6 %, respectively. Protein-like, alcohol-phenol, and biodegradable aliphatic substances were metabolized by bacteria during the thermophilic phase, and accumulation of humus-like substances increases the relative concentration of aromatic compounds. <i>Caldicoprobacter</i> was discovered to be an important contributor to the degradation and formation of DOM. DOM concentration (33.4 %) and temperature (17.7 %) were the main environmental factors that promoted bacterial community succession.	(Ma et al., 2022)
<i>Hermetia illucens</i>	Larvae were harvested and dried in a conveyer oven at 60 °C to a moisture content of 5 % - 8 % for optimum biodiesel conversion.	Food waste	Extracted oil can be used to make high-quality biodiesel, because it contains a high concentration of medium-chain saturated fatty acids (67 % total fatty acids), and a low concentration of polyunsaturated fatty acids (13 % total fatty acids). The feed value of black soldier fly larvae (i.e., prepupae, pressed cake, and meal) was comparable to commercial feed sources.	(Surendra et al., 2016)
<i>Hermetia illucens</i>	Food waste mixed with coir pith for optimum bioconversion. Water is used to keep the substrate hydrated.	Food waste	After bioconversion, the crude protein content was 41.44 ± 0.17 g/100 g and the crude lipid content was 35.69 ± 0.24 g/100 g. The conversion ratio of bio-waste to larvae was 6:80, with a bioconversion efficiency of $24.31 \pm 0.62\%$. Overall, the substrate reduction was $72.38 \pm 1.37\%$.	(Ebenezar et al., 2021)
<i>Hermetia illucens</i>	Food waste blended with wheat bran for improved bioconversion.	Household food waste (cuttings and peelings of fruit and vegetables, grounded tea, rice, noodles, and chicken eggshells)	Biosolids blended with other organic waste, such as food waste or wheat bran, improved larvae performance (40 % substrate reduction after 20 days; <149 kg larvae/tonne dry substrate) and fat content (<31 %).	(Bohm et al., 2022)
<i>Hermetia illucens</i>	Maize straw fermented with <i>Aspergillus oryzae</i> in a 4000:1 ratio for 24 hours for maximum bioconversion. Wheat bran was used as the control feed.	waste straw	The dry larvae harvested contained 41.76 % crude protein, 30.55 % crude fibre, and 8.24 % crude ash. When compared to the control diet, the fly larvae had a higher proportion of monounsaturated fatty acid (24.86 %) and polyunsaturated fatty acid (25.37 %), but a lower proportion of saturated fatty acid (45.41 %). Maize straw had a dry matter reduction of 48.41 %.	(Gao et al., 2019)
<i>Musca domestica</i>	Mixed-level orthogonal array design for optimal breeding of housefly larvae. Variables selected for optimal breeding a) substrate ration (Staple food waste and dish waste at 1:0, 3:1, 1:1, 1:3, 0:1) b) breeding density c) feeding mood (one-time feeding, daily feeding, and feeding on demand)	Food waste in restaurants	The following conditions were optimal for housefly larvae to convert food waste: culture substrates ratio 1:3, breeding density 10.0 g/kg, and all substances added on the first day. The optimal food waste mass reduction rate ranged from 79.1 % to 83.6 %.	(Cheng et al., 2021)

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Table 2 (continued)

Insect Species	Tactics Used for Optimum Bioconversion	Organic Waste	Main Findings	References
<i>Musca domestica</i>	<i>M. domestica</i> combined with microbes (<i>Corynebacterium variabile</i>) to produce biomass and organic fertilizer from gibberellin fermentation residue (GFR). The following optimized solid-state fermentation conditions were used to remove gibberellic acid A3 from GFR: 60 % GFR, 40 % rice straw powder, pH 8.5, and 6 days at 26°C.	Gibberellin fermentation residue	(0.83 %) values in housefly larvae products met the Food and Agricultural Organization (FAO) requirements for feed protein. The crude fat content (30.1 ± 1.18 %) was higher than the crude fat content (22 %) of housefly larvae after bioconversion of pig manure and the Chinese fish meal standard. GFR can be a great alternative to animal feed protein sources with 56.4 % protein, 21.6 % fat, and several essential amino acids. From 3500 g raw GFR mixture containing 400 g rice straw, 371 g housefly larvae meal, and 2064 g digested residue was bio-converted. GFR, with 3.2 % total nitrogen, 2.0 % inorganic phosphorus, 1.3 % potassium, and 91.5 % organic matter, could be used as an organic fertilizer.	(Yang et al., 2015)
<i>Musca domestica</i>	Food waste (700 g) and adjuvant (300 g) were used. The humidity of 70–80 %, pH 5–7, and temperature of 25–30°C were maintained. Stirring after every 6 h for proper ventilation.	Food waste from restaurants mixed with adjuvant (millet bran, whole plant corn silage, wheat bran and sawdust)	Protein and oil were the two most important value-added products with 57.06 ± 2.19 % and 15.07 ± 2.03 % respectively. Wheat bran was found to be the most suitable adjuvant.	(Niu et al., 2017)
<i>Musca domestica</i>	Rearing conditions were temperature 28 ± 2 °C, RH 50 – 60 %, 14:10 light/dark photoperiod. Flies were kept in cubical mesh cages (30 cm × 30 cm × 45 cm).	Fermented crop straw (Corn, wheat, wheat bean)	Corn straw diet showed highest bioconversion with 16.19 %. In fermented agricultural straw diets, the weights of cellulose, hemicellulose, and lignin significantly dropped.	(Qi et al., 2019)
<i>Tenebrio molitor</i>	Air humidity was kept at 60 %±4 % for <i>T. molitor</i> to ensure healthy insect development. The temperature in the rearing environment was 22.5±2.5°C, and the humidity was 60 % ±4 %, with a 12:12-h light/dark cycle.	10 % chicken feed complemented with 90 % vegetable waste, garden waste, cattle manure, or horse manure	<i>T. molitor</i> grew at 22.5±2.5°C when it was 71–101 days old. <i>T. molitor</i> had a high-fat content.	(Harsányi et al., 2020)
<i>Tenebrio molitor</i>	Insects were kept in a rearing facility at 28°C, 55–60 % RH and 12 h photoperiod. Plastic containers (35 × 23 × 13 cm) were used as cages with aeration holes.	Chicken feed, rapeseed meal, wheat bran, and willow leaf sunflower	Insects grown on wheat bran showed the highest values of larvae with the shortest development time (77.4 d). The lowest feed conversion was shown by rapeseed meal.	(Bordiean et al., 2022)
<i>Tenebrio molitor</i>	<i>T. molitor</i> larvae was raised in polypropylene plastic containers (11.8 cm × 8.8 cm × 6.2 cm) and containers were placed in a biochemical incubator at 27±1°C temperature and 60 % humidity. Substrate wheat bran was spiked with AFB ₁ .	Wheat bran	<i>T. molitor</i> weight rose from 138 g to 469 g, or around 103 g of protein, per kg of wheat bran infected with AFB ₁ . <i>T. molitor</i> bioconverted AFB ₁ to produce 13 metabolites in the frass and three metabolites in the larvae. <i>T. molitor</i> can be employed to provide valuable larval protein and handle grain contamination more effectively.	(Zhao et al., 2022)
<i>Zophobas morio</i>	Air humidity and temperature were 60 % ± 4 % and 22.5±2.5°C, respectively with 12:12 h light/dark cycle for healthy development.	10 % chicken feed complemented with 90 % vegetable waste, garden waste, cattle manure, or horse manure	Larvae reached maximum weight after 90 days. Fat content was found to be high.	(Harsányi et al., 2020)

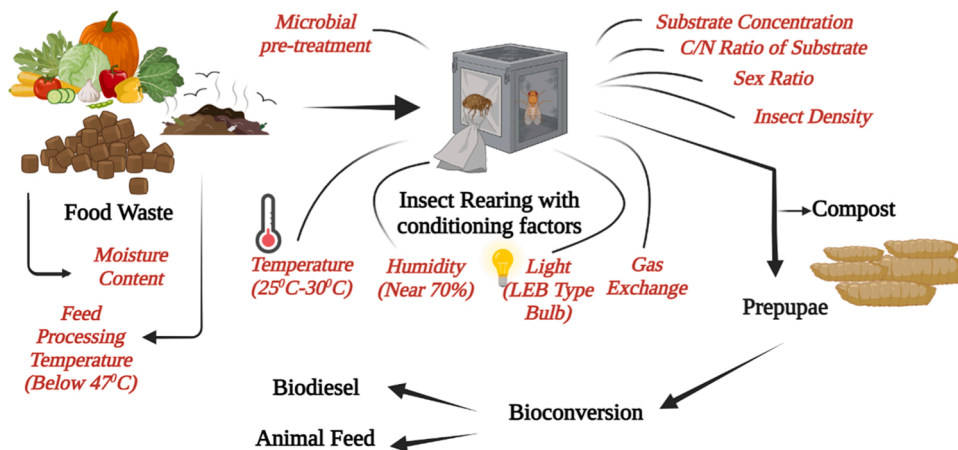


Fig. 2. Process of bioconversion along with conditioning factor for rearing system.

on the situation, prepupae can then be transformed into bio-products or animal feed.

4.1. Effect of temperature and moisture content

Temperature plays a significant role in insects' growth, survival, and weight gain, directly leading to waste bioconversion efficiency. In a previous study, BSF was reared at three different temperatures (e.g., 20, 25, and 30 °C) and two substrate moisture conditions (natural and 70 % substrate moisture) until 50 % of the larvae reached the prepupal stage (Eberle et al., 2022). It was shown that 70 % moisture content and temperature ranging from 25 to 30 °C are suitable for higher bioconversion and BSFL development (Ribeiro et al., 2022). Similarly, Shumo et al. (2019) studied the effect of temperature on BSFL development, survival, and bioconversion. Five temperatures (e.g., 15, 20, 25, 30, and 35 °C) were considered during the study, with 25–300 °C being the optimum range. The longevity of adult BSF was decreased as temperatures rose, while female fecundity was increased (Shumo et al., 2019).

4.2. Diet type and composition

Diet type and composition can be vital in bioconversion efficiency (Sandrock et al., 2022). Bioconversion efficiency and production can vary depending on the content and type of the diet (Arabzadeh et al., 2022). Vegetable processing industries generate massive amounts of byproducts, and it is critical to efficiently rear BSF on various substrates to ensure an economic advantage in bioconversion and overcome the seasonality of some leftovers (Fuso et al., 2021).

Diet can affect larval performance, nutritional composition, and the effectiveness of waste reduction in addition to frass features. Compared to BSFL raised on the Gainesville diet as a reference, larvae raised on a waste-based diet (fruit, vegetable, and bakery waste-based diet supplemented with brewery waste) performed better in terms of individual larval mass (162.11 mg), bioconversion rate (13.32 %), and proximal larval composition, which included higher dried matter (28.49 %) and lipid (35.99 %) and lower ash content (4.22 %) (Arabzadeh et al., 2022). This bioconversion process waste frass has high macro- and micro-nutrient values comparable to commercial organic fertilizers in horticultural production (Bohm et al., 2023). The diet implemented here was based on the plant source, and the waste-based diet performed much better than the reference diet (Arabzadeh et al., 2022).

Nitrogen source and carbon to nitrogen (C/N) ratio significantly affect BSF larvae development and the waste bioconversion process. In a past study, nitrogen supplying effects of nine nitrogen species, such as NH₄Cl, NaNO₃, urea, uric acid, Gly, L-Glu, L-Glu: L-Asp (1:1), soybean flour, and fish meal were considered, and their ration to carbon in the diet was also studied for larval development and bioconversion efficiency. The results indicated that NH₄Cl and NaNO₃ led to poor survival and growth of BSF larvae. C/N of 18:1–14:1 improved waste reduction and larvae production performance, and C/N of 18:1–16:1 improved larval protein and lipid bioconversion, whereas C/N of 12:1–10:1 caused a significant performance decline (Akbarzadeh et al., 2015). So, C/N ratio adjustment is a viable approach for waste bioconversion (Lu et al., 2021). BSF can co-digest soybean curd residue and kitchen waste to significantly increase larval yield, bioconversion rate, and lipid bioaccumulation (Li et al., 2022). Co conversion technique is very useful for fibrous cellulose rich organic waste conversion to biomass (Li et al., 2022).

Combinations of insects and organic waste can improve and optimize bioconversion efficiency. For growth and survival rates, as well as nutritional value, 10 % chicken feed supplemented with 90 % vegetable waste, garden waste, cattle manure, or horse manure was used on *Z. morio*, *T. molitor* and *A. domesticus* and mashed chicken feed was used a reference diet (Harsányi et al., 2020). As a result, it was found that high percentage of mixed vegetable waste, garden waste with green biomass of several species, or cattle manure and horse manure is not

suitable for larval production compared to chicken feed. With increasing fat content protein content was decreased in all three insect species due to diet type (Harsányi et al., 2020). Coconut fibre, corncob powder, and Brewer's and Torula yeast mixture are potential substrates for *Drosophila suzukii* larval development. The flies developed in the coconut fibre and Brewer's yeast diet produced the most pupae per gramme of the diet and had the highest bioconversion (6 %) (Aceituno-Medina et al., 2020).

Larval development, survival, yield, protein conversion (PrCR) and bioconversion rate (BCR), substrate mass reduction (SMR), and body composition of the insect were investigated in two rearing densities of BSF with beverage by-products such as coffee grounds (SCG), brewer's spent grains (BSG) and their mixtures with the addition of brewer's yeast (BY) as diet (Sideris et al., 2021). The analyses showed that feeding on BSG + BY and SCG + BSG + BY resulted in better bioconversion and larval growth along with SMR, PrCR, and BCR. Larval density only affected crude protein percentage. Fibrous diets were discovered to be favorable for bioconversion, whereas SCG alone was not.

Poultry feed, food waste and manure can be used for BSF for waste valorization and more sustainable global protein supplies (Sandrock et al., 2022). Okara (a byproduct of soymilk production), maize distillers, and brewer's grains were used as BSF diet to check performance on biomass production, SMR, nutritional profile and *in vitro* digestibility, and larval gut microbiota with hen diet as control. The highest larval biomass was collected on maize distillers, while okara had the highest SMR. The lauric acid content of BSF larvae reared on okara was lower (17.6 % of total fatty acids). Maize distillers had the highest *in vitro* crude protein digestibility (87.8 %) (Saleh et al., 2003). A significant increase in bacterial complexity in the gut microbiota of larvae fed with poultry feed was shown (Galassi et al., 2021). The agro-industrial byproducts are appropriate for BSF larvae rearing. They exhibit high chemical variability (crude protein, ether extract, neutral detergent fibre, etc.), affecting the larvae's performance, composition, and nutritional value (Abd El-Hack et al., 2020; Spranghers et al., 2017; Eke et al., 2023).

Using animal feed as substrates to grow BSF larvae in terms of larval growth rate, waste reduction index (WRI), and conversion efficiency of ingested feed can be beneficial. BSF larvae and biowaste conversion were evaluated in triplicate in the following biowaste substrates: chicken feed (CF; reference diet), pig manure solid (PMS), Betafert® solid (BTFS), swill (SW), olive pulp (OP), pig manure liquid mixed with chicken feed (PMLCF), and silage grass (SG). The highest growth rate was found in larvae reared on SW (13.4 mg/d) as compared to the reference substrate CF (7.2 mg/d), and the growth rate of BTFS, OP, and SG was meagre (0.6, 0.2, and 0.7 mg/d, respectively). SW had the highest WRI (11.3), followed by PMLCF (9.3). The highest CO₂ and the lowest NH₃ were found in larvae with the highest growth rate (Veldkamp et al., 2021). This study confirmed that low-value products like animal feed could also be a very suitable option as a substrate for biomass production.

Comparison of growth performance, feed conversion ratio, and efficiency of ingested feed of *T. molitor* was studied using chicken feed, rapeseed meal, wheat bran, and willow leaf sunflower as substrate. The wheat bran diet shows the fastest and highest development of larvae in 74 d. rapeseed meal showed the lowest feed conversion ratio (Fasce et al., 2022). Except for wheat bran, other substrates can be used as a byproduct with a control diet (chicken feed 100) to grow *T. molitor* (Bordiean et al., 2022).

Due to their high availability and excellent bioconversion efficiency, organic waste such as food scraps, vegetable waste, and plant-based diets are appropriate for bioconversion and biomass production (Sanchez Matos et al., 2021). Maintaining the C/N ratio in the substrate for better bioconversion can be done using nitrogen sources, especially organic ones. One of the sources that work best for C/N balancing is urea. Fibrous foods like wheat bran, corncobs, maize straw, coconut fibre, brewer's yeast, and others are best for co-conversion and produce excellent outcomes. Agro-industrial byproducts like cattle, horse, and

poultry manure and feed like chicken, hen, and poultry feed, among others, can be constructive for producing high-protein biomass to fulfill the protein requirement of today's world and can be a sustainable approach for protein production (Sanchez Matos et al., 2021).

Larval protein production can be done via aflatoxin metabolism. Wheat bran was spiked with aflatoxin B₁ (AFB₁) and used as a substrate for bioconversion by *T. molitor*. AFB₁ was detoxicated and eliminated using phase I metabolism, which included reduction, dehydrogenation, hydration, demethylation, hydroxylation, decarboxylation, and keto reduction, followed by phase II metabolism, which involved conjugation of amino acids, glucosides, and glutathione. Per kilogram of wheat bran infected with AFB₁, *T. molitor* weight increased from 138 g to 469 g, or approximately 103 g of protein. AFB₁ was bio-converted by *T. molitor* into 3 and 13 metabolites in the frass and larvae, respectively (Zhao et al., 2022). *T. molitor* can deliver essential protein to larvae and better handle grain contamination (Zhao et al., 2022).

4.3. Effect of egg loading

The impact of common housefly (*M. domestica*) egg loading on waste reduction and maggot development was studied. Housefly larvae were raised on three different diets, including wheat bran, millet bran, and cow dung, at four egg loads (1.25, 2.5, 5, and 10 mg). With increasing egg load under the same nutritional conditions, the yield of housefly larvae, the number of larvae, and the reduction of substrates all increased. Rearing egg load of 10 mg and wheat bran substrate were found to be most effective. According to this study, the egg load, substrate type, and their interactions impact on the larval biomass, larval number, egg viability, and substrate rate reduction of *M. domestica* (Leyo et al., 2021).

4.4. Light conditioning

When it comes to indoor breeding systems, artificial light systems can be an excellent boon for the successful bioconversion of organic waste. Liu et al. (Liu et al., 2020) studied the effect of a halogen lamp (HL), a combination of a white light-emitting diode (LED) lamp and a fluorescent ultraviolet lamp, a metal halide lamp, and a specially designed light-emitting diode (BSFLED) lamp on the bioconversion by BSF. Spectral sensitivity of the photoreceptors of the compound eyes of the adult BSF was a key parameter for the study. BSFLED yielded the highest number of inseminated females and fertile egg clutches with the highest mating success ($90.0 \pm 5.8\%$) and the highest production of fertile egg clutches ($91.4 \pm 5.3\%$) (Liu et al., 2020).

BSF commonly occurs in sub-tropical and warm temperate climates and matting typically depends on space and sunlight. BSF is very sensitive to cage size and artificial lighting, but recent studies proved that rearing is possible under artificial lighting (Chia et al., 2018). The effect of three artificial light sources, namely LED, fluorescent lamps, and HL, on small-scale indoor rearing was investigated to compare oviposition traits (i.e., pre-oviposition period, total oviposition period, and egg mass per female) and half-life of BSF. LED source was found to be suitable for artificial rearing (Heussler et al., 2018).

Another study looked at the effect of lights (mix of LED (UV: blue: green 1:1:3), white LED, and neon light) and nutrients (i.e., sugar and water, only water, and no sugar no water) on adult performance. Light played a secondary role as compared to the prime role of nutrients and a mix of LED light sources resulted in the best performance of BSF (Macavei et al., 2020). Hoc et al. (2019) experimented on BSF reproduction by taking sex-ratio, density, and nycthemeral cycle (2, 6, 12, and 18 h of daily light) into consideration. Exposing BSF to increasing light duration resulted in early oviposition and was associated with a decrease in the oviposition period (Hoc et al., 2019).

4.5. Effect of bacteria

Bacteria can also have a big influence on the rearing system of insects and bioconversion rate. Dairy manure (DM) and chicken manure (CHM) (2:3) were bioconverted using BSF and cellulose degrading exogenous bacteria, resulting in structural and chemical modification of fibers (Rehman et al., 2019). *Lactobacillus buchneri* was used with soybean curd residue (SCR) to see the efficiency BSF in reducing environmental pollution and conversion of SCR to biomass for high-quality animal-derived proteins and fats for human and livestock consumption. SCR was pretreated with *L. buchneri* (10^8 CFU/mL) before converting with BSF larvae. SCR and *L. buchneri* fed BSF larvae had significantly higher dry mass reduction ($55.7 \pm 0.9\%$), bioconversion rate ($6.9 \pm 0.3\%$), crude protein content ($55.3 \pm 0.6\%$), and fat content ($30.0 \pm 0.6\%$) (Somroo et al., 2019). *Corynebacterium variabile* was used with BSF to convert gibberellin fermentation residue (GFR) to biomass by removing gibberellic acid residue A3 (Yang et al., 2015).

5. Industrial utilization of bioconversion insects and their by-products

Insect-based bioconversion is considered an environmentally friendly approach to waste management compared to the conventional methods. Insect-based bioconversion can transform large quantities of organic waste into valuable products such as feed for animals, food for people, secondary industrial compounds (biofuel, lubricants, pharmaceuticals, dyes, among others), and soil amendment (Fig. 3) (Fowles and Nansen, 2019b).

Thus, mass production of insects for feed and secondary products has seen exponential growth in the sector (van Huis and Oonincx, 2017). Previous reports have shown that insects have a lower feed-to-protein conversion ratio than conventional livestock, and they emit fewer greenhouse gases and ammonia emissions than any conventional livestock (Nikkhah et al., 2021; van Huis, 2022a; Wang and Shelomi, 2017). In addition to the benefits already described, some insect species have physiological characteristics that make them more suitable for commercialization, such as a high rate of reproduction, a short life cycle, quick growth, and ease of handling and manipulation.

5.1. Food and feed

With the rapidly growing human population coupled with the uncertainties of climate change, the demand for sufficient food and feed is of great concern (Dragojlović et al., 2022). It is estimated that the world population in 2050 will be about 9 billion, which could lead to a high food demand (Zielińska et al., 2015). The conventional sources of protein such as livestock production will not be sufficient for the rising global population. Moreover, there is an urgent need to enhance the quality of meals worldwide, guaranteeing adequate nutrient provision while avoiding contributing to the global epidemic of obesity and accompanying chronic diseases such as diabetes, cardiovascular disease, and gastrointestinal malignancies (Hawkey et al., 2020). In general, edible insects are thought to be a good source of protein, lipids, essential nutrients, vitamins, and minerals that may be produced on low-value feeds and have a minimal carbon footprint (Gasco et al., 2020). Insects provide between 5–10 % of animal protein sources and supply fats, calories, vitamins, and minerals for human consumption (Hernández Toxqui et al., 2021).

Rearing insects on organic wastes and feeding them to livestock can increase their protein content and at the same time reduce the emission of greenhouse gases. The nutritional value of some bioconverter such as *H. illucens*, *M. domestica*, *T. molitor*, *Z. morio*, *L. migratoria* and *S. gregaria* has been reported to be an alternative protein and lipid sources in various animal feeds (Mudalungu et al., 2021; Wang and Shelomi, 2017). Table 3 describes the nutrient content of some bioconverter insect species considered food and feed sources, with energy contents

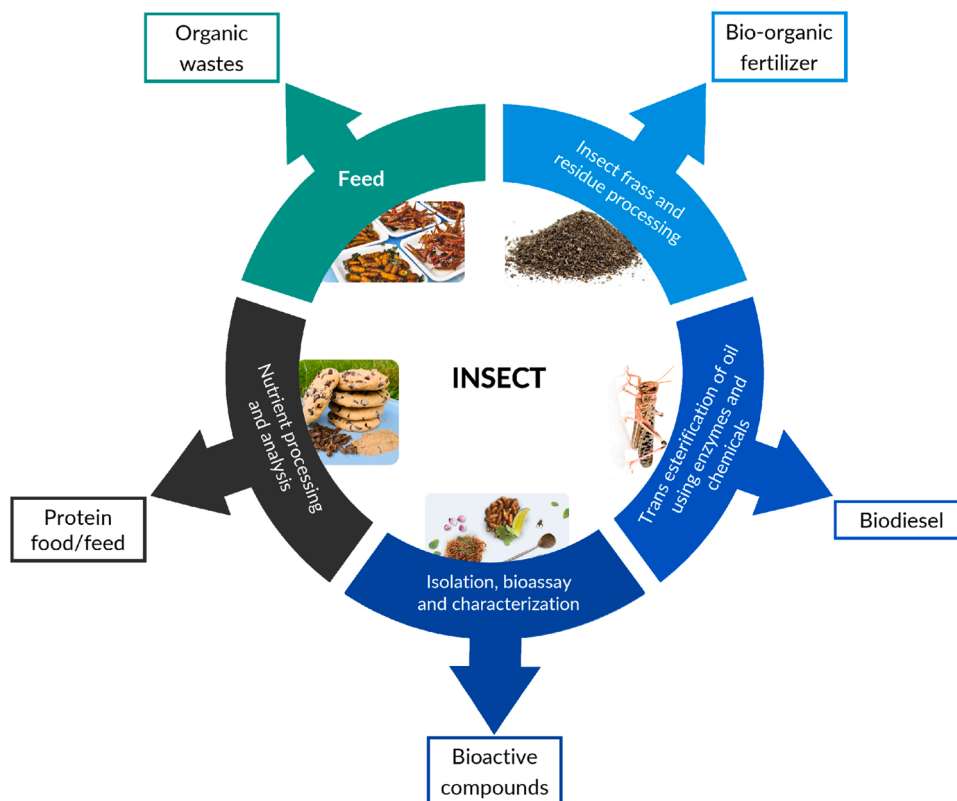


Fig. 3. Schematic presentation of bioconversion of organic waste to biofuel, biofertilizer, bioactive compounds and animal feed.

being comparable to other protein-rich sources. Insect meals are also more prevalent in aquafeed due to the modulatory effects they have on aquatic animals' immune systems and gut microbiota balance (Huyben et al., 2019). *H. illucens* is a rich source of Omega-3 fatty acids and thus, considered suitable for fish foods (Wang and Shelomi, 2017). Sealey et al. (Sealey et al., 2011), reported that, there were no significant differences in fish growth and vision development when fish feed prepared from *H. illucens* was compared to the normal fish meal for feeding the rainbow trout, *Oncorhynchus mykiss*. The medium chain saturated fatty acids make up about 67 % of the total fatty acids in *H. illucens*-derived oil, whereas polyunsaturated fatty acids make up 13 % of the total fatty acids. *T. molitor* and *Z. morio* are considered the most important sources of protein and fat in poultry feed (Benzertih et al., 2020; Kierończyk et al., 2018). The insect is reported to have high crude protein and lipid contents with essential amino acids, fatty acids as well as antimicrobial peptides (Benzertih et al., 2020). Oil made from *T. molitor* is considered a substitute for soybean oil, which is frequently used in broiler chicken nutrition. A poultry diet prepared from *T. molitor* causes a favorable effect on the fatty acid profile of breast muscle and the expression of specific genes, such as GIMAP5 and APOA1 which are responsible for regulating hematopoietic integrity, and lymphocyte homeostasis and phenotypic fatness variability respectively (Kierończyk et al., 2018).

A previous study reported that, replacing fish meal up to 30 % with a defatted *Z. morio* diet did not compromise growth performance and feed utilization in rainbow trout, *O. mykiss* (Hosseini Shekarabi et al., 2021). Broiler chick diets have also included *M. domestica* maggots which give similar or better growth rates compared with conventional poultry feed (Sanchez-Muros et al., 2016).

5.2. Biofuel/biodiesel

Considering the world's rapid population and economic growth, the demand for efficient energy and improved living standards have put tremendous stress on the environment and conventional energy sources

(Wang and Shelomi, 2017). For the past century, fossil fuels have been the main energy source (86.4 %) for global economic growth (León et al., 2022). It is estimated that between 2012 and 2020, the global use of oil and other liquid fuels would increase from 90 million barrels per day (b/d) to 100 million b/d, and to 121 million b/d by 2040 (Wang and Shelomi, 2017). However, the depletion of non-renewable fossil fuels and concerns about climate change have driven the development of environmentally friendly renewable energy sources, including solar, wind, and tidal energy and biomass-based bioenergy (Elliston et al., 2016). Biofuels such as bioethanol and biodiesel are renewable energy that are considered alternative energy sources due to their environmental advantage. The main barrier preventing biodiesel from being used as a primary fuel is the cost of production (Priya et al., 2021). About 75 % of the cost of production emanates from the feedstock which are mostly agricultural crop (Sanchez-Muros et al., 2016; Sánchez-Muros et al., 2014). Moreover, with the effects of climate change, these crops are considered scarce food source. In Europe, Southeast Asia and the USA, rapeseed oil, palm oil and soybean oil are the main material for biodiesel production (Zheng et al., 2013). Using scarce food resources for biodiesel production are not a sustainable for energy generation. Using environmentally friendly and sustainable energy source has led to a global policy shift toward renewable and low-cost raw materials such as biomass for energy generation (Yang et al., 2016). Recent research has concentrated on the use of alternate sources, such as insect fat (Nguyen et al., 2017), microbial lipid (Salama et al., 2017), and waste oil (Pollardo et al., 2018), for the generation of biodiesel.

Currently, the use of insect to degrade organic waste to accumulate fat-based biomass are gaining ground due to its economically feasibility, availability of insects, their high fat production and environmentally friendly (Mohan et al., 2023; Siddiqui et al., 2022; Su et al., 2019; Wang and Shelomi, 2017). Some insects can degrade organic wastes, thus serving as a potential feedstock for biodiesel production (Su et al., 2019). Many insect species including *H. illucens*, *M. domestica*, and *T. molitor* that generate fat have been identified for use in the

Table 3
The nutrient content of some bioconverter insect species and effects on farmed animals.

Insect Species	Insect part used for feed	Crude protein (% DM)	Fiber (% DM)	Total fat (% DM)	Ash (% DM)	Energy (MJ/kg DM)	Animal feed	Main Findings	References
Coleoptera									
<i>Tenebrio molitor</i>	Larvae	46–54	2–5	25–36	3–4	27	Chicken	Improve the fatty acid profile of breast muscle and the expression of specific genes, such as GIMAP5 and APOA1 in poultry	(Kierończyk et al., 2018)
							Pig	Weaned pigs' body weight gain, feed consumption, and crude protein digestibility were observed to increase when soy was partially replaced with <i>T. molitor</i>	(Jin et al., 2016)
<i>Zophobas morio</i>	Larvae	47	-	44	8	-	Rainbow trout	Total carotenoid content and redness of rainbow trout fillet were improved when fed with diet prepared from <i>Z. morio</i>	(Hosseini Shekarabi et al., 2021)
							Gilthead seabream	High rates of survival. No negative impact on feeding behaviour, body weights, or specific growth rates	(Rumbos and Athanassiou, 2021)
Diptera									
<i>Hermetia illucens</i>	Larvae	34–42	7	25–58	4–20	22–24	Rainbow trout	Improved fish growth and vision development when rainbow trout were fed with the meal prepared from the insect	(Sealey et al., 2011)
							Jian carp	The growth performance of Jian carp fed with <i>H. illucens</i> was similar to feed prepared from soybean	(Li et al., 2016)
<i>Musca domestica</i>	Larvae	51–60	6–7	25–28	11–20	20–23	Chicken	Broiler chick diets made from <i>M. domestica</i> gave a similar growth rate as conventional poultry feed made from soya	(Sanchez-Muros et al., 2016)
Orthoptera									
<i>Acheta domesticus</i>	Adult	59–72	5	10–23	5	-	Dog	No adverse effects on hematology, blood chemistry, body weight, body condition score, feed intake, faecal output, faecal score, faecal moisture, or apparent total tract digestibility were observed when dogs were fed with diet prepared from <i>A. domesticus</i>	(Areerat et al., 2021)
<i>Schistocerca gregaria</i>	Adult	76	2.53	12.97	3.33	18	Chicken	Sensory attributes of poultry meat appeared to be improved. <i>S. gregaria</i> diets had higher crude protein digestibility than the control fish meal.	(Nginya et al., 2019)
Plant source									
Soybean meal		55.2	4.4	1.7	7.3	20			(Hawkey et al., 2020)
References for the nutrition composition of the insects		(Hawkey et al., 2020; Shahida Anusha Siddiqui et al., 2022)							

manufacturing of biodiesel (Wang et al., 2017). The biorefinery study using *T. molitor* yielded 8.50 g of insect biomass with a waste dry mass reduction rate of 51.32 % and a 1.95 g crude grease from larval biomass that produced 1.76 g biodiesel using corn stover substrate (Wang et al., 2017). A direct transesterification using methanol and n-hexane was shown to be effective in producing biodiesel yield of 94.14 % from biomass of *H. illucens* larvae (Nguyen et al., 2017). Lauric acid methyl ester (35.5 %), oleic acid methyl ester (23.6 %), and palmitic acid methyl ester (14.8 %) were the main ester components of the resultant biodiesel. *H. illucens* fat-based biodiesel had a similar fuel characteristic to rapeseed oil-based biodiesel, including density (885 kg/m³), viscosity (5.8 mm²/s), ester concentration (97.2 %), flash point (123 °C), and cetane number (53) (Li et al., 2010). About 21.6 % of crude grease was obtained when *M. domestica* larvae was reared on swine manure which yielded a 90.3 % conversion rate of triglycerides to its esters. The biodiesel obtained from the larva biomass had density (881 kg/m³), viscosity (5.64 mm²/s), ester content (96.8 %), flash point (145 °C), and cetane number (52) (Yang and Liu, 2014). Insect-based biodiesel production has a great potential to meet the growing demand for liquid fuels, especially in developing continents. It will cut fossil energy consumption, relieve the impact on the environment, and reduce the cost of biodiesel. According to a previous study by Zheng et al. (Zheng et al., 2013) and Siddiqui et al. (2022), most of the biodiesel produced using bioconverter were of high-quality and met most of the EN14214 standards (Table 4). The advantage of biodiesel from these insects is that the

process involves fewer carbon emitting factors (Mohan et al., 2023).

5.3. Fertilizer

As the world's population grows and embraces lifestyles that use environmentally intensive food products, soil and water resources continue to be under intense pressure (Schmitt and de Vries, 2020). To produce crops and animals to feed the growing global population, a supply of fertilizer rich in phosphorus (P) and nitrogen (N) is now necessary. Interestingly, the conventional methods of fertilizer production are not environmentally friendly (Johnson, 2023). Moreover, increased losses of N and P to the atmosphere and water because of nutrient inputs have had several detrimental effects, including eutrophication of freshwater, and coastal marine ecosystems and hazardous algal blooms (Schmitt and de Vries, 2020). Coastal marine ecosystems provide several facilities for human well-being, such as cultural (e.g., recreation, tourism) and regulating services (e.g., climate regulation, coastal protection, erosion control, carbon sequestration) (Lakshmi, 2021). Nevertheless, these ecosystems are sensitive to anthropogenic stressors (e.g., population growth, urbanization, and environmental degradation) and environmental change, consequently, it is crucial to preserve their health through a sustainable management (Hu et al., 2019). Health equity should be considered while tackling the dangers brought on by climate change, global urbanization, and urban environmental health hazards including infectious diseases in a globalized

Table 4

Comparison of biodiesel properties from *Hermetia illucens*, *Tenebrio molitor*, *Musca domestica* and two other sources.

Properties	<i>Hermetia illucens</i> biodiesel	<i>Tenebrio molitor</i> biodiesel	<i>Musca domestica</i> biodiesel	Rapeseed biodiesel	Waste cooking oil biodiesel
Density (kg/m ³)	860–895	860	881	880–911	877
Viscosity at 40 °C (mm ² /s)	4.9–6.0	NA	5.64	4.4–5.8	5.23
Sulfur content (wt %)	NA	NA	NA	<0.01	NA
Ester content (%)	96.5–97.2	96.8	96.8	NA	NA
Water content (mg/kg)	300	300	NA	300	NA
Flash point (°C)	123–128	127	145	NA	157
Cetane index	53–58	58	52	45	48
Acid number (mg KOH/g)	1.1	NA	NA	0.3	0.21
Methanol or ethanol (m/m)	0.3 %	0.2	NA	NA	NA
Distillation (°C)	360	NA	NA	352	NA

NA = data not available. Properties of the biodiesel obtained from the insects are comparable to rapeseed biodiesel and waste cooking oil. Data are retrieved from (Siddiqui et al., 2022; Yang and Liu, 2014; Zheng et al., 2013).

society (Krefis et al., 2018). Therefore, by fostering sustainable and resilient ecosystems, lowering environmental risks, and enhancing access to basic goods and services for all, collaborations among coastal marine ecosystems, urban ecology, and urban ecosystems can support gender mainstreaming, human health, and well-being. An important step in addressing the consequences of excess N and P is to identify sources that are exogenously sourced rather than endogenously derived from the food chain and returned to it. Although, livestock manure is rich in biodegradable organic matter and nutrients, if not managed well can become an important source of pollution (Nie et al., 2015). Also, the current composting techniques used to produce manure are further challenged by the low C/N ratio, high moisture content, unpleasant odor, lengthy decomposition duration, nutrient loss, and the generation of phytotoxic chemicals (Xiao et al., 2018). Alternative environmentally friendly and sustainable approaches are consequently important to maximize the incorporation of fertilizers generated from manure in crop production.

Many naturally occurring organisms can transform organic waste including manure into beneficial nutrients such as nitrogen, phosphorous, and potassium that are helpful for crop production a typical example been insect-derived biofertilizer (Fowles and Nansen, 2019b; Sarpong et al., 2019; Xiao et al., 2018). The frass produced by insects' larvae while feeding on organic waste is rich in N and P and thus can be incorporated into the production of biofertilizers (Schmitt and de Vries, 2020). A well-studied insect used for the convention of organic waste to biofertilizer is *H. illucens* (Kawasaki et al., 2020; Quilliam et al., 2020; Sarpong et al., 2019; S.A. Siddiqui et al., 2022; Xiao et al., 2018). The insect can process large volumes of organic waste and can feed on a wide range of organic substrates (Lalander et al., 2019). The advantage of insect-generated biofertilizer over the conventional composite is that the insect frasses can modify the soil microbiome and plant behavior due to the high concentration of chitin derived from the insect (Poveda et al.,

2019). Previous studies revealed that the frass composition of *H. illucens* was N (3.39 %), P₂O₅ (2.85 %) and K₂O (3.47 %) which was able to positively affect the plant development (Schmitt and de Vries, 2020). Economically, producing the insect derived biofertilizer can be more profitable than producing biogas or composting because the process that creates it also results in the production of proteins, fats, and other products that can be sold for relatively high prices (Schmitt and de Vries, 2020).

5.4. Bioactive compounds from insects

In many parts of the world, the use of insects as medicine (entomotherapy) is a significant substitute for contemporary therapy (Seabrooks and Hu, 2017). Health-promoting antioxidants, angiotensin-converting enzyme (ACE) inhibitors to treat high blood pressure and effects on hyperlipidemia and fat reduction in humans are all benefits of bioactive substances found in insects (van Huis, 2022a). ACE inhibitory peptides are one of the bioactive compounds discovered in insects with health advantages. The ACE inhibitory peptides insects may provide are crucial for controlling blood pressure and maintaining cardiovascular health (Cito et al., 2017). In vitro research has demonstrated that insects belonging to the Diptera, Coleoptera, Lepidoptera, Hymenoptera, and Orthoptera orders are a potential source of ACE inhibitory peptides (Cito et al., 2017).

Numerous therapeutic qualities, such as antioxidant and anti-platelet aggregation action, have been examined in vitro in various edible insects (Table 5). A recent study found that short-chain fatty acid synthesis and viability in nutrient-stress circumstances were improved by flour from *T. molitor*, which in turn influenced the growth of *Lactobacillus* and *Bifidobacterium* (D'Antonio et al., 2021). Also, studies with obese mice have shown that *T. molitor* larvae extract has the potential for humans to reduce diabetes type II (Seo et al., 2017). α -Pyrone, diketopiperazine, and chitin isolated from *H. illucens* pose antimicrobial properties against *Staphylococcus aureus* and *Pseudomonas aeruginosa* (Mudalungu et al., 2021). When *H. illucens* was fed with food wastes, 40 S ribosomal protein S4, 60 S ribosomal protein L8, ATP synthase subunit alpha, ribosomal protein S3, Histone H2A, NADP-glutamate dehydrogenase, fumarate hydratase, RNA helicase, chitin binding peritrophin-A, lectin C-type protein were produced. Furthermore, functional analysis of the proteins revealed that the 60 S ribosomal protein L5 (RpL5) in the larvae of *H. illucens* interacted with a variety of ribosomal proteins and played a key role in the glycolytic process (AT14039p) (Lu et al., 2022). Venom, notably from bees, has been investigated as an alternative treatment for inflammation and cancer therapy (Lee et al., 2015). Pedrin and cantharidin isolated from the rove and blister beetles have been reported to be a potential anticancer candidate (Puerto Galvis et al., 2013). Moreover, A global social and health emergency is antibiotic resistance. It is crucial to look for therapeutic substitutes, such as the use of antimicrobial peptides (AMPs) (Di Somma et al., 2022; Manniello et al., 2021; Moretta et al., 2020; Scieuzo et al., 2023b). Moretta et al. (Moretta et al., 2020) utilized different machine-learning algorithms to predict the AMPs activity from *H. illucens*. Fifty-seven putatively active peptides were identified from the transcriptomes of *H. illucens*, showing various combinations of antimicrobial, anticancer, antiviral, and antifungal activities. A study conducted by Manniello and collaborators (Manniello et al., 2021) demonstrated that insect antimicrobial peptides (AMPs) have shown potential as an alternative to antibiotics. In addition, AMPs showed promising outcomes in terms of reducing bacterial load and changing microorganism structures in infection sites. In this sense, Brevinin-2Ta and Ltx-109 (synthetic antimicrobial peptidomimetic) demonstrated a decrease in bacterial load and faster angiogenesis and granulation tissue maturing process, comparable to classical antibiotics (Moretta et al., 2021). A novel recombinant AMPs, C-15867, derived from *H. illucens* has been also proposed as an alternative to current antibiotics by Somma et al. (Di Somma et al., 2022). The study demonstrated the strong antimicrobial effect of the C-15867 peptide on

Table 5

Bioactive compounds isolated from some bioconverter insects.

Insect	Compound isolated from	Isolated compound	Biological activity	References
Blattodea <i>Macrotermes</i> spp.	Adult body surface	Roseoflavin, 8-methylamino-8-demethyl-D-riboflavin, Natalamycin, and Termisoflavones A-C	Antibacterial and antifungal	(Zhou et al., 2021)
Diptera <i>Hermetia illucens</i>	Larvae hemolymph	α -pyrone, Diketopiperazine, and Chitin	Antibacterial	(Mudalungu et al., 2021)
Coleoptera <i>Zophobas morio</i> and <i>Tenebrio molitor</i>	Larvae	Chitin and Carotenoids	Antimicrobial, prebiotic properties.	(Dragojlović et al., 2022)
Orthoptera <i>Brachystola magna</i>	Adult	Pancratistatin, Narciclasine, and Ungeremine	Anticancer	(Seabrooks and Hu, 2017)
<i>Schistocerca gregaria</i>	Adult gut	Desmosterol, (3 β , 5 α) cholesta-8, 14, 24-trien-3-ol, 4, 4-dimethyl, (3 β , 20 R) cholesta-5, 24-dien-3, 20-diol, Quercetin, and Luteolin	Antimicrobial properties under investigation	(Cheseto et al., 2020, 2015)
<i>Acheta domesticus</i>	Adult	4-hydroxybenzoic acid, p-coumaric acid, Ferulic acid, and Syringic acid	Antioxidant	(Nino et al., 2021)

bacterial strains, including *E. coli* BL₂₁ and *S. aureus*.

Numerous microbial endophyte species, such as bacteria and fungi, are hosts for insects. These endophytic microbes may be participating in or cooperating with their insect hosts to produce the natural substance (e.g., terpenoids, flavonoids, alkaloids) mentioned with biological effects, such as antibacterial, anti-insect, anti-cancer, among others (Seabrooks and Hu, 2017). In fact, insect-derived compounds have much potential for natural product medicine development if given the correct consideration. In addition, the antioxidant potential of insect extracts appears promising, and more research needs to be done on other insect bioactive compounds. Molecules isolated from some bioconverter insects, and their biological activities are summarized in Table 5. The techniques for recovering these bioactive compounds vary according to the endophytic bacteria and the organic material generated.

6. Methods for processing the insects

Nutrition upcycling of waste biomass involves using food waste to obtain high-quality digestible micro- and macronutrients that can be reintroduced into the food chain. For use in the feed industry, insects are regarded as having a high nutritional value and are believed to be a sustainable source of protein. Particularly in aquaculture, they are rapidly being used to replace traditional protein sources. Valorization of agricultural and industrial by-products is one of the most important areas in which they have the potential to be used readily, and it is also one of the essential fields. Insects are a fantastic choice for managing organic wastes and the upcycling of nutrients because of their ability to convert a wide array of food waste sources (Mannaa et al., 2024; Hameed et al., 2022). For insects to be used as a source of nutrition for farmed animals, there must first be a conversion from organic materials to insects and then another conversion from insects to farmed animals (van Huis, 2022a, 2022b). This comes at a time when there is a growing desire to develop a circular economy on a global scale. The most effective utilization of feed with minimal opportunity costs currently in use in the European Union is capable of producing 31 g of animal protein per person daily (van Hal et al., 2019). While maximizing the nutritional content essential for cattle development through the direct upcycling of waste biomass nutrients is possible, this is significantly hampered by the many components in waste streams (Zhao et al., 2022, 2023). Insect-based bioconversion has the potential to obtain a stable nutrient composition in its biomass. This stable nutrient composition has the added benefit of being able to be adapted to the needs of individual users and effectively included in feed formulations. Upcycling nutrients through insects ensures a stable macronutrient composition that may be integrated into feed formulations (Ravi et al., 2020).

Insect processing varies from one use case to the next, from whole-

insect ingestion to the intake of biomolecules derived by appropriate separation. Insects collected through natural harvesting or mass-reared on a commercial scale can improve their nutritional value, sensory appeal, and shelf life using several methods (Melgar-Lalanne et al., 2019). These days, manufacturers use a mix of traditional and new processing methods. Blanching, drying, grinding, roasting, and fractionating are employed in insect processing (Ojha et al., 2020). However, this is only part of the list. In response to the growing demand for insects on a global scale, a diverse range of insect-based goods can be manufactured through the use of a variety of alternative processing methods, including fermentation, salting, and non-thermal technologies (Ojha et al., 2020). In addition, commercial thermal processing, low-temperature processing, and fermentation technology are also prominent approaches (Liang et al., 2023). Each approach has pros and cons, and not all edible insects or insect flours can be processed using all procedures (Liceaga, 2021). While there is room for expansion in the food and feed sectors' use of insects and their contents as techno-functional and bio-functional agents, drying technologies have received relatively little attention in terms of original research and patents. Traditional societies rely heavily on sun drying, while the scientific community and the Western market favor freeze drying. Other approaches like oven and microwave-assisted drying have been investigated on a larger scale (Prabhu et al., 2023). However, there were scant accounts of how these factors affect food safety and the presence of bioactive substances, as well as their potential financial benefits or drawbacks (Hernández-Álvarez et al., 2021). The techniques and treatments commonly used to process edible bioconverter insects are summarized in Fig. 4.

6.1. Blanching

Blanching is used as a pretreatment in most industrial methods for producing edible insects, both on a small and large scale (Melgar-Lalanne et al., 2019). This is done to inactivate degradative enzymes and eliminate harmful microbes that might cause food poisoning or spoilage. The food is removed from the boiling water and quickly chilled with ice or cold running water to stop the thermal treatment. Blanching in hot water, on the other hand, has proven to be less effective against mesophilic bacterial spores, which was to be expected (Alp and Bulantekin, 2021). Hot water blanching can dramatically lower total mesophilic bacterial counts, total psychrotrophic bacterial counts, lactic acid bacterial counts, and yeast and mold counts in insects (Caparros Megido et al., 2016).

Acheta domesticus and *G. assimilis* were subjected to freeze-drying, oven-drying, and blanching to analyse the effects of the various processing methods on the plants' nutritional and physical properties. Nevertheless, *A. domesticus* and *G. assimilis* might have different

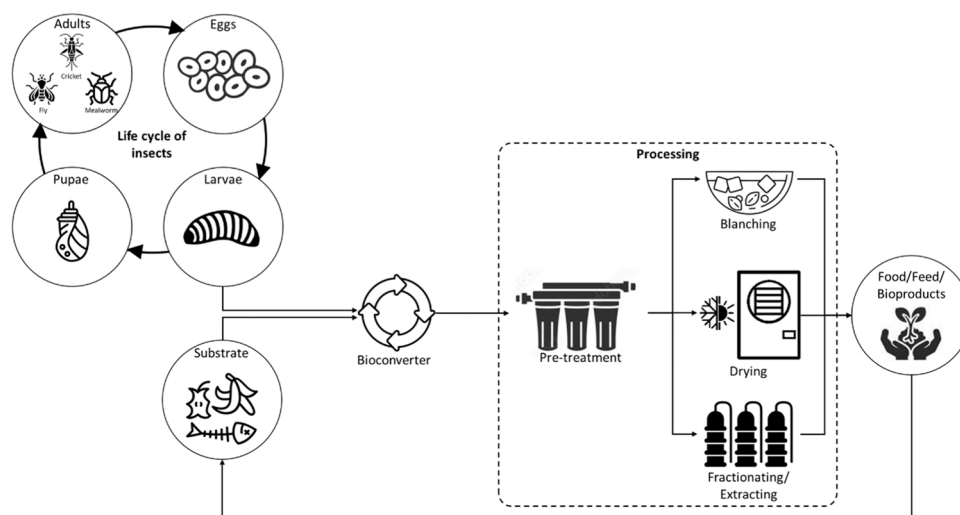


Fig. 4. Methods for processing the insects.

microbiological and toxicological profiles according to their developmental stage, gender, nutrition, physicochemical variables, and processing techniques (Khatun et al., 2021). The nutrient composition of *A. domesticus* and *G. assimilis* comprises high protein contents, essential amino acids, polyunsaturated fatty acids, and minerals (e.g., iron, zinc) (Jucker et al., 2022). These insects' microbiological and toxicological profiles vary on how they are raised and processed; thus, evaluating them is crucial to ensure they are safe to eat (Mlček et al., 2018). Although the use of regional organic wastes as a substrate for insect growing can support sustainable and circular food production systems, it is important to carefully consider how these byproducts affect these insects' nutritional content and composition (Iguar et al., 2020; Mlček et al., 2018). Although these three strategies did not impact proximate composition, fatty acid profiles, or amino acid profiles, they did influence other parameters for both species (Iguar et al., 2020). The treatment affected vitamin B12 levels in *G. assimilis*, but not in *A. domesticus*. The lightness and browning index of both kinds of cricket were improved by freeze-drying. After oven drying, blanching, and freeze drying, both species of crickets showed lower levels of lipid oxidation than before. Freeze-dried crickets had more fatty acid oxidation volatiles, while oven-dried crickets had Maillard reaction products (Khatun et al., 2021). Although freeze-drying produced better color, oven-drying and blanching produced better nutritional and flavor qualities (Khatun et al., 2021).

Wet mode fractionation (WMF) was investigated as a potentially new and sustainable method for BSFL. The juice and press cake of BSFL were obtained via steam blanching and pulping. After the BSFL juice had been exposed to additional treatment, including homogenization, enzyme incubation, and centrifugation, four separate BSFL fractions were extracted. For a WMF procedure, the total energy usage was 0.321 kWh. Most of the components of BSFL juice were water and solids (Ravi et al., 2021). Lipids from BSFLs mostly consisted of lauric and linoleic acid. Compared to other treatments, the emulsion stability and foam capability of the proteins in the aqueous fraction came out on top (Heuel et al., 2021). The solid fraction contained 40 % of the chitin content, whereas the juice press cake maintained 60 %. The major components' amino acid profile and WMF process fraction distribution were explored (Ravi et al., 2021).

In BSF, mechanical pressing separated the exoskeleton, while sonication and enzymatic treatment were used to fractionate the slurry. Muscle fibers were seen to be firmly connected to the peripheral fat bodies under the microscope. Fat extraction was reduced by 25.0 % after blanching compared to a 3.3 % decrease in the absence of blanching. This was due to protein aggregation and fat trapping in the protein

matrix (Azzollini et al., 2020). After centrifuging the juice extracted from the unblanched larvae, three distinct layers were separated: a cream layer high in lipids and proteins, a supernatant containing soluble protein, and a pellet containing primarily insoluble proteins. The centrifugation of the blanched juice resulted in forming of a lipid fraction, a thinner cream layer, and an increased pellet. Although sonication had no impact on the fractionation process, the enzymatic treatment led to the solubilization of pellet protein and an enhanced lipid layer. In conclusion, complete larvae can have more lipids (>80 %) extracted as a cream layer by processing without blanching. In contrast, a clear lipid layer (>40 %) can be extracted through blanched-enzymatic treatment. For both samples, centrifugation resulted in roughly 50 % protein recovery in the pellet and 50 % in the residual (Azzollini et al., 2020).

Tenebrio molitor and *Z. morio*, classified as edible insects, were treated with four pH solutions and two distinct blanching processes. In addition, the larvae underwent two different heat treatments, after which they were contrasted with fresh, unblanched larvae (Cacchiarelli et al., 2022). The findings showed that the enzymatic browning process might be slowed down or stopped entirely by employing blanching techniques and modifying the pH of the solution. Blanching reduced enzymatic browning in both species, whereas acidification at pH 2 helped. Blanching also influenced microbiological characteristics (Cacchiarelli et al., 2022). They reduced bacterial burden in both species compared to freshly collected larvae, enhancing hygiene and safety (Cacchiarelli et al., 2022).

6.2. Drying

The drying process is one of the most widely used techniques for extending how much food retains its freshness. Drying can be accomplished in several ways, some dating back to antiquity while others are more contemporary and cutting-edge. Because drying lowers the total water content and activity, less free water is available for degradative enzymatic activities and the formation of microbial communities (Alp and Bulantekin, 2021). Insects that have been dried are less dangerous to transport and have a longer storage life than insects that have not been dried (van Huis et al., 2013). Drying whole edible insects, flours, and powders can be accomplished through several processes, including drying in the sun, drying in an oven, and freezing (Azzollini et al., 2018). It has been stated that one of the recommended technologies for increasing the number of insects that people in western countries consume is first to dehydrate the insects so that they are entirely edible and then grind them into a powder so that they can no longer be recognized as insects (Melgar-Lalanne et al., 2019).

The frozen fraction of BSFL exhibited the highest degree of protein solubility across the board regarding pH. The value of the nitrogen-to-protein conversion and the aminogram content of dry-defatted BSFL flour, concentrate, and isolate were all measured and calculated. The antioxidant capabilities of water-soluble bioactive compounds discovered at BSFL were investigated. Compared to the other fractions, the microwave-assisted subcritical treatment and the freezing-devitalized BSFL fraction exhibited superior radical scavenging capacity and total polyphenol content, respectively. Acetylation characterized chitin fractions. Devitalization methods greatly affect the principal BSFL elements except for chitin. Therefore, the approach should rely on the insect product's eventual use (Ravi et al., 2020).

Freeze-drying was the most effective method for preserving protein, certain minerals, and vitamins compared to hot air drying, oven broiling, roasting, pan frying, deep frying, boiling, steaming, and microwaving as processing methods (Fröhling et al., 2020). After being microwaved, the vitamin B1 and B3 concentrations were the lowest, and after being deep fried, the total mineral content was the lowest. Mealworms have total phenolic contents and levels of antioxidant activity that follow patterns that are very similar to one another (Baek et al., 2019).

Alternate heating treatments were utilized to minimize the microbial load of *A. domesticus* based on conventional process conditions for producing *A. domesticus* flour. Additionally, drying temperature and duration were manipulated to ascertain whether the required residual moisture of 5% may be obtained more rapidly while maintaining consistent microbiological purity. Finally, under ideal conditions, researchers investigated how the processing conditions affected the *A. domesticus* microbial community as it moved through the processing chain. Through all stages of processing, the total number of CFU/g DM that are still alive was reduced from 9.24 to 1.98 log₁₀ (logarithmic) (Fröhling et al., 2020). The *A. domesticus* flour was negative for Bacillaceae, Enterobacteriaceae, Enterococcaceae, yeasts, and molds but positive for Staphylococcaceae and mesophilic spore-forming bacteria. These findings highlight the importance of steaming as a processing step for effectively boosting microbiological safety (Fröhling et al., 2020).

Dry fractionation produced protein-enriched and differentially constituted yellow mealworm larvae fractions in this investigation. Post-harvest operations such as blanching, freezing, drying, and defatting affected the larvae's physicochemical characteristics. The post-harvest process chain altered the dried larvae's color, size, apparent density, and hardness, affecting fractionation behavior and properties (Purschke et al., 2018). Drying at high temperatures triggered browning reactions and tissue collapse, darkening and shrinking the material. Mechanical properties were also impacted, resulting in heterogeneous particle size distributions following milling and sieving. Freeze-dried and defatted larvae had a high percentage of particles <500 μm (Purschke et al., 2018). The sieving fractions had significant variations in macronutrient composition (Purschke et al., 2018).

6.3. Fractionation/extraction

Protein from insects can be more widely used in human meals as a powder, supplement, or fraction. There is potential for a wide range of uses of insect protein in human diets, which the manufacturing of protein-rich insect flour can expand for integration into foods. Water, organic solvents, and enzymes can all be used to extract macromolecules from insects. Although various matrices and solvents can affect extraction rates, yields, and physicochemical qualities differently, these factors are not universal (Bußler et al., 2016). Many methods of extracting macromolecules from insects have been tried. However, they all require using large quantities of chemical solvents that are neither safe for the environment nor edible (Soetemans et al., 2019). Due to rising customer demand for chemical/additive-free materials, "green" and "clean" extraction methods are gaining popularity (Tiwari, 2015).

The development of reliable technologies for the recovery of insect

protein is a prerequisite for increasing its application in industrial settings (Ma et al., 2023). The recovered protein can potentially replace traditional protein sources like fishmeal and soybean meal in animal production as a feed supplement). Extracting protein directly from insect flour can be challenging, especially because of its high lipid content (Hasnan et al., 2023). Even basic separation methods such as centrifugation or decantation can unintentionally extract lipids into the solvent medium. However, insect proteins like BSF larvae and mealworms are uniquely soluble in acidic conditions, specifically at pH 2, which can be even better than their solubility in alkaline conditions in some cases (Ma et al., 2023). Raising the temperature from 20 to 60 °C has also enhanced protein recovery for defatted BSFL flour (Bußler et al., 2016). The influence of solubilization pH, centrifugation speed, and centrifugation length on the protein recovery of *T. molitor* larvae was investigated in a previous work that utilized a centrifugal fractionation technique (Raihan et al., 2019). The recovery ranged from 31% to 58%, and the larvae contained more protein as they grew (Harrison et al., 2021). The findings of this study provide a database that can be used in the design of commercial separation processes by explaining the major factors that influence the effectiveness of the centrifugal separation stage in mealworm protein concentration and recovery (Purschke et al., 2018).

High hydrostatic pressure processing has been utilized recently to enhance the functional characteristics of proteins. Insect meals from two commercial sources (*G. sigillatus* and *T. molitor*) and their corresponding Alcalase®-generated hydrolysates were tested for their functional qualities under standard conditions and after being pretreated under pressure (Dion-Poulin et al., 2020). Enzymatic hydrolysis did not affect water binding capacity, foaming, or gelation qualities across insect species and treatments. The quick instability of the emulsion after enzymatic hydrolysis led to poor emulsion properties. Mealworm meal's degree of hydrolysis was likely reduced due to protein denaturation and aggregation events caused during pressurized pretreatment. Unsurprisingly, the solubility increased dramatically after enzymatic digestion (under and without pressure). While pressurization pretreatment increased the solubility of mealworm meal compared to the control hydrolysate, it lowered the solubility of cricket meal (Dion-Poulin et al., 2020).

7. Challenges of insect-based bioconversion

Insect rearing is a relatively new industry, and commercial farming of insects still needs to catch up to traditional livestock farming. Many international institutions and companies, including Agriprotein (Cape Town, South Africa), Bioflytech (Alicante, Spain), Co-Prot (Phnom Penh, Cambodia/Rotterdam, the Netherlands), Enterra Feed (Vancouver, Canada), Enviroflight (Yellow Springs, OH, USA), Protix (Dongen, the Netherlands), and the Swiss Federal Institute of Aquatic Science and Technology (Dübendorf, Switzerland), have been working on the development of actual industrial scale production of insect larvae for animal feed (Pastor, 2015).

Smaller *M. domestica* and blowflies' production systems for feed have also been developed in Africa and Asia by the Guangdong Entomological Institute (Guangzhou, China), Huazhong Agricultural University (Wuhan, China), Institut d'Economie Rurale (Bamako, Mali), Fish for Africa, and the University of Stirling (Accra, Ghana) (Charlton et al., 2015). These farms have already commercialized fly meals, proteins, or fats extracted from fly larvae. However, current production is insufficient to meet the expected demand for animal feed and faces significant economic challenges due to the high cost of biomass production.

Sustainability is now a significant issue for human beings due to the increasing daily population, increasing and inefficient use of resources leading to climate change, loss of biodiversity, environmental pollution, health issues, and poverty (Cadinu et al., 2020). To maintain quality food and manage organic waste, insect rearing, and bioconversion of waste will be critical parameters. Most proteins produced and consumed

globally are produced in unsustainable, linear food systems from production to disposal, resulting in significant nutrient losses. Insect-rearing and bioconversion are promising strategies for converting lost nutrients into protein-rich animal feed and fertilizer (Law and Wein, 2018). Overcoming challenges such as human and social acceptance, production facility development and the requirement of manpower and technology, along with legal and political support, will be critical (Pastor, 2015). Fig. 5 shows some challenges associated with bioconversion with the help of insects.

7.1. Human acceptance and production technology and manpower

Human acceptance of insects and insect-based products is the primary challenge in modern societies. Even though the concept of edible insects is very old, there is still a strong dislike for feed containing ingredients derived from insect biomass, particularly in Western countries. Public awareness is critical for overcoming this type of challenge, and political decision-makers, researchers and entrepreneurs, international agencies, and the food and feed industries should cooperate to ensure the success of the awareness campaign (Cadinu et al., 2020).

Developing proper methods, suitable infrastructure, and add-on technology is undoubtedly a big issue regarding the bioconversion of organic waste. Industries should come forward to partner with academic or research organizations to overcome this problem and develop working models and technology that are scalable to the industry level. Factors like insect selection for bioconversion, their growth stage, reproduction cycle, breeding conditions, and feeding need to be optimized for better bioconversion and rearing of insects (Law and Wein, 2018).

Operational parameters, such as pH, larval density, food-to-larvae ratio, temperature, nitrogen conversions, and feeding rates, should be optimized for the best bioconversion. Biowastes like fruit waste, vegetable waste, and faecal should opt for micronutrient characterization need to be compared with conventional feed like chicken feed or Gainesville diet to find out digestibility, energy content, amino acids and fatty acids, vitamins, and minerals (Cammack and Tomberlin, 2017; Spranghers et al., 2017). For example, in collaboration with industry, sensitivity analysis was performed to determine the potential magnitude of environmental impact reduction in the insect industry (Smetana et al., 2019). A Dutch firm recently developed a centralized system for dispersing olfactory triggers to control oviposition in BSF adult colonies.

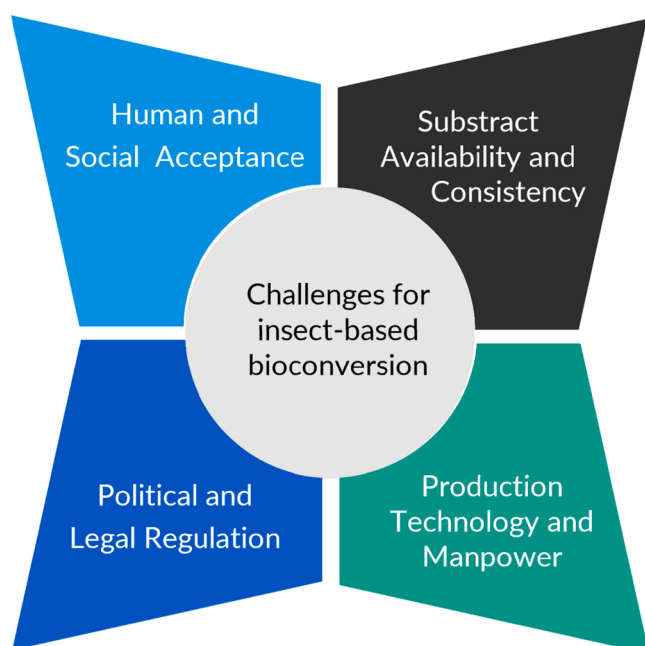


Fig. 5. Challenges associated with insect-based bioconversion.

An automated device has also been designed to transport newborn larvae from the adult cage to a system allowing for their counting, dozing, and analysis. The same company also patented a breeding cage with pipes for receiving and discharging cleaning liquids to improve the effectiveness of any cleaning process (Jansen, 2017).

Production is very labor-intensive; generally, higher labor costs and land scarcity are prominent in urban areas relative to non-urban areas. With a viable and optimized technology, automation is required to achieve the sustainable bioconversion of biowaste. Process engineering practices, including monitoring and modelling need to be implemented to achieve a smooth running of the bioconversion system, just like wastewater treatment, anaerobic digestion, and bioethanol production to obtain a smooth cost-effective automated bioprocess (Cadinu et al., 2020; Law and Wein, 2018; Pastor, 2015; Surendra et al., 2020).

7.2. Substrate availability and consistency

The availability and consistency of substrate are critical factors in bioconversion, especially financially. Organic waste availability is relatively high in urban areas as compared to rural areas. However, factors like load, nutrients, organic and moisture content and texture, and non-organic contaminants like plastic can be critical in choosing the substrate and getting consistent results (Spranghers et al., 2017).

Larval growth rates and separation of mature larvae from the frass depends on the moisture content of the feed (Cammack and Tomberlin, 2017). Standardization of feed processing is essential to maintain the temperature below the lethal range of 47°C, especially for a high nutrient and moisture content diet. Quality control and equalization of waste with physical and biological methods like homogenization and pre-fermentation are significant to maintain the stability and safety of feed along with particle size (<10 mm) and moisture content (40–80 %) of feed (Gupta et al., 2018).

Pathogens present in the food is also a major concern. Food pathogens that might be in the substrate may get into the intestinal tract of the larva and then infect individuals who eat the resulting animal products or traditional farm animals that are fed a BSF-based feed. On the other hand, BSF larvae have antimicrobial properties and can reduce pathogenic bacteria such as *Salmonella spp.* and *Escherichia coli* in the substrates (Wynants et al., 2019).

Environmental temperature and humidity, quantity and quality of larval diet, quantity and quality of adult diet, mating, adult population density, age of flies, oviposition substrate, photoperiod and genetic factors all contribute to the number of eggs a female can oviposit (Pastor, 2015). Device can be designed that can stimulate the oviposition to get the maximum number of eggs from the flies. Fish, pork or beef liver or blood is the most used substrates to stimulate oviposition in Calliphoridae and Sarcophagidae, as these flies require animal protein for ovary development, whereas pollen can be used as an oviposition stimulant in hoverflies. To obtain the greatest number of eggs, the adult cages must be filled with an optimal number of pupae (Yang and Liu, 2014).

7.3. Political and legal aspect

The political aspect plays a vital role in the bioconversion process. The government must be convinced about the food and bioconversion process product, especially for animals. Academia and industries should unite to convince the political leader to establish and support bioconversion facilities and public awareness (Siva Raman et al., 2022). The emphasis would have to be on generating revenue by producing high-quality, consistent downstream products in terms of larvae size, appearance, and nutritional content. Another primary consideration is waste transportation costs, so farming operations may need to use a combination of centralized and decentralized facilities, with the bioconversion unit close to the waste source.

Legal regulations are essential for the advancement of insect farming

and the effective marketing of insect-based foods. Insects are called 'impurities' in the Codex Alimentarius, a collection of international food safety standards (Baiano, 2020). Because insects are not regulated as food in the United States, the FDA does not grant insects or insect-based ingredients as Safe status (Center for Food Safety and Applied Nutrition, 2018). For regulation of insects, insect parts, or insect derivatives as a food additive, USFDA approval is required. However, manufacturer can self-certify the product as safe under GRAS (Generally Recognized as Safe) (Boyd, 2017). Loblaw's, Canada's largest grocery chain, began selling cricket powder under its private label after Canada determined in 2017 that crickets (*G. sigillatus*) were not a novel food. Consumer-Packaged Goods companies only sometimes prefer self-certification for large-scale production with prior approval of FDA GRAS (Li et al., 2022). Only very few selected insects are allowed by EU regulation based on their pathogenic characteristic, whether they are invasive or not, do they cause any diseases to humans or animals and any adverse effect on crops along with whether they are protected or not. According to Commission Regulation (EU) 2017/893 of May 24, 2017, amending Annexes I and IV to Regulation (EC) No. 999/2001 of the European Parliament and the Council and Annexes X, XIV, and XV to Commission Regulation (EU) No. 142/2011 in terms of the provisions on processed animal protein, the following insect species meet safety conditions for insect production for feed use: *H. illucens*, *M. domestica*, *T. molitor*, *A. diaperinus*, *G. sigillatus*, *A. domesticus*, and *G. assimilis* (European Union., 2017; Żuk-Golaszewska et al., 2022).

Expansion and diversification are limited due to the regulatory guidelines. Regulations in Europe, the United States, and Canada restrict the production of BSF to vegetable-based pre-consumer food waste (including dairy and eggs), and the resulting products can only be used as feed for fur-producing animals, pets, and aqua-cultured fish (Abd El-Hack et al., 2020). The European Commission is currently investigating the possibility of proposing a new revision of the feed ban rules to allow pig and insect proteins in poultry feed when reared on vegetative substrates (Surendra et al., 2020). Some recent legal documents regarding insect food, feed and bioconversion are listed in Table 6.

Like livestock, food and, feed safety are two major concerns for edible insects. The regulatory framework needs to address the production chain, like wild harvesting and farming of insects, as these two are the primary type of production. Many legal regulations (Regulation (EC) No. 1069/2009; Commission Regulation (EU) No. 142/2011; Commission Regulation (Implementing Regulation (EU) 2017/2469) address hygiene standards in feed and food production (European Union, 2021a). Competent authorities assess the newly introduced product, such as the Veterinary Inspectorate or the Sanitary Inspectorate.

For food safety, the quality of harvested insects and the presence of residues and contaminants should be tested regularly per Codex Alimentarius recommendations. For edible insect products, the product must comply with feed and food hygiene standards, good breeding, and hygiene practices followed by good production practices. The substrate used for the edible insect market should be acquired within the plant or animal-based material like livestock. HACCP (Hazard Analysis and Critical Control Point) principles and European feed laws are two competent authorities that certify manufacturers for commercial feed market sales (Żuk-Golaszewska et al., 2022). Insects sold as food or feed must meet microbiological safety standards, maximum residue limits (MRL), and the absence of undesirable chemical substances such as heavy metals, pesticides, and mycotoxins (Bosona and Gebresenbet, 2013). All insect protein (PAP) containing feeds were withdrawn from the market due to transmissible spongiform enteropathies, and the EU recently lifted the ban on using PAP from one animal species in feeds intended for other animal species (European Union, 2021b; Żuk-Golaszewska et al., 2022).

The insect market is growing tremendously; as of 2021, the market capitalization is about 10,000 metric tons, and by 2030, it is expected to reach half a million metric tons. Growth will depend on sustainability and functional benefits such as palatability and health. High costs and

Table 6
Recent legal documents regarding insect food, feed, and bioconversion.

Name of the Documents	Year	Reference
Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods, amending Regulation (EU) No. 1169/2011 of the European Parliament and of the Council and repealing Regulation (EC) No. 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No. 1852/2001.	2015	(European Union, 2015a)
EFSA Scientific Opinion "Risk profile related to the production and consumption of insects as food and feed" issued 8 October 2015	2015	(EFSA, 2015)
IPIFF information document "Regulation (EU) 2015/2283 on novel foods- Briefing paper on the provisions relevant to the commercialisation of insect-based products intended for human consumption in the EU.	2015	(European Union, 2015b)
Commission Regulation (EU) 2017/893 of 24 May 2017 amending Annexes I and IV to Regulation (EC) No. 999/2001 of the European Parliament and of the Council and Annexes X, XIV and XV to Commission Regulation (EU) No. 142/2011 as regards the provisions on processed animal protein	2017	(European Union., 2017)
Commission Implementing Regulation (EU) 2017/2469 of 20 December 2017 laying down administrative and scientific requirements for applications referred to in Article 10 of Regulation (EU) 2015/2283 of the European Parliament and of the Council on novel foods.	2021	(European Union, 2021a)
'Novel Food' Report: Opinion on the Risk Profile for House Cricket (<i>Acheta domestica</i>) by the Swedish University of Agricultural Sciences (EFSA funded report, adopted on 6 July 2018).	2018	(Fernandez-Cassi et al., 2018)
Commission Notice—Guidelines for the feed use of food no longer intended for human consumption C/2018/2035.	2018	(Żuk-Golaszewska et al., 2022)
EN ISO 22000: 2018 on food safety management systems.	2018	(ISO, 2021)
Commission Regulation (EU) 2021/1372 of 17 August 2021 amending Annex IV to Regulation (EC) No. 999/2001 of the European Parliament and of the Council as regards the prohibition to feed non-ruminant farmed animals, other than fur animals, with protein derived from animals	2021	(European Union, 2021b)

prices, limited production capacity, and legislation are the main drawbacks to exponential growth. Efficiency and development RandD, with proper legislation, capital investment, and marketing, can improve the insect industry for a better sustainable world (van Huis, 2022b).

8. Remarks and future perspectives

Organic waste management has become a global burden because of its environmental and human health effects. The rapid world population growth, economic development, and urbanization will require substantial resources to meet the potential high demand for food and organic waste management. Insect-based bioconversion has been proposed as a viable approach to managing organic waste mainly due to the less energy input and less harmful gases generated. Insect-based bioconversion of organic waste offers an exciting opportunity for more sustainable and novel paths for waste management. This process has been shown to be more sustainable than microbial bioconversion because this requires a controlled environment and specific conditions to be effective. In addition, microbial bioconversion can produce methane, a potent greenhouse gas, during the anaerobic digestion (Naser El Deen et al., 2023). Moreover, some bioconverter insects are edible. Edible insects are considered an excellent alternative source of protein, lipids, essential nutrients, vitamins, and minerals that may be produced on low-value feeds and have a minimal carbon footprint.

Insects are now more widely accepted as a healthy dietary option and a more sustainable alternative to conventional meat products. Moreover, insect-based bioconversion can be carried out under controlled conditions, reducing the risk of disease outbreaks (Naser El Deen et al., 2023). The bioactive compounds in bioconverter insect extracts are of tremendous interest and will be crucial in the future for the commercial viability of insect mass cultures. The insect industry will experience significant expansion over the coming years, creating jobs, innovative commodities, new feedstock inputs, and ultimately reducing and reusing food waste streams currently viewed as hazardous. However, substantial research is still required to (i) determine the efficacy and safety of newly developed insect products, (ii) increase the efficiency of converting organic waste to insect biomass, (iii) develop effective insect-based technologies to optimize the mass production, processing, marketing of edible and biofuel production, and (iv) develop a breeding program to create specialized insect strains for effective bioconversion. Furthermore, if we want to realize these benefits in our agricultural system in the upcoming years, insect frass also has obvious benefits and problems that require an increase in research support. Nowadays, the insect industry suffers from the absence of a comprehensive legal framework. It is therefore recommended that countries should develop specific criteria for edible insects and their byproducts. Insect-based bioconversion of organic waste has the potential to reduce waste, generate employment, provide novel products, and provide a sustainable source of protein to help feed the world's expanding population.

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CRediT authorship contribution statement

All authors listed have significantly contributed to the development and the writing of this article. S.A.S. – Conceptualization, Methodology, Validation, Formal Analysis, Writing - Original Draft, Writing - Review and Editing, Data curation, Investigation, Visualization, Project administration, Resources, Supervision. I.A.H. – Writing - Original Draft. J.O.O. – Writing - Original Draft. T.S. – Writing - Original Draft. Y.S.W. - Writing - Review and Editing. I.F. – Writing - Review and Editing. R.P. – Writing - reviewing and editing. J.S.C. – Writing - Review and Editing.

Author contribution

All authors listed have significantly contributed to the development and the writing of this article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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