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REVIEW

Enhancing the bioconversion rate and end products of black soldier fly (BSF) treatment – A comprehensive review

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Abstract
Food security remains a pressing concern in the face of an increasing world population and environmental challenges. As climate change, biodiversity loss, and water scarcity continue to impact agricultural productivity, traditional livestock farming faces limitations in meeting the growing global demand for meat and dairy products. In this context, black soldier fly larvae (BSFL) have emerged as a promising alternative for sustainable food production. BSFL possess several advantages over conventional livestock, including their rapid growth, adaptability to various organic waste substrates, and low environmental impact. Their bioconversion rate, the ability to transform organic waste into valuable products, and final product optimization are key factors that enhance their potential as a nutrient-rich protein source, fertilizer, and biofuel. This review explores strategies to enhance the bioconversion rate and improve the end products derived from BSF treatment. It highlights the benefits of using BSFL over other interventions and underscores the significance of optimizing their bioconversion rate to meet the challenges of global food security sustainably. Despite the promising prospects of BSF-derived products, consumer acceptance and regulatory hurdles remain critical aspects to address in realizing their full market potential. The utilization of BSFL as a sustainable source of food and feed can contribute to waste management, reduce environmental pollution, and address the pressing issue of food security in an environmentally responsible manner. However, there is a need for further research and innovation to ensure the safety, quality, and economic viability of BSF-based products for both animal and human consumption.

Keywords Food security · Organic waste · Consumer acceptance · Waste management · Environmental pollution

1 Introduction

Food security is a major issue in today's world with more than one billion people lacking sufficient dietary energy (Wudil et al., 2022). Food security is vital to humans and meeting the world's growing demand for meat, milk, and dairy products, land and water is becoming increasingly difficult (Davis & White, 2020). An emission-mediated climate change

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together with biodiversity loss and the spread of plant pests and diseases will significantly affect future food production and caloric availability, increasing the prevalence of child malnutrition (Harttgen & Seiler, 2023). However, while the productive agricultural land on our planet is decreasing due to extreme climate and unpredicted weather, the world population and food demand are growing. The world's population is projected to be in excess of 9.7 billion people by 2050 (Gu et al., 2021).

Agricultural productivity becomes more sensitive as temperatures rise with major implications for poverty and food security (Alemu & Mengistu, 2019). Additionally, extreme events such as floods and droughts can also affect food security (Ebi & Bowen, 2016). Rising temperatures offset increased crop growth and yields while leading to increased pest infestations, shorter harvest times, and changes in the growing season (Srinivasa Rao, 2023).

The production of certain products requires large amounts of water but water scarcity is becoming a major problem hindering the expansion of global food production (Ngxumeshe et al., 2020). Agriculture consumes about 70% of the world's fresh water and climate change is exacerbating this (Albert et al., 2021). The production of fertilizers has a major impact on environmental degradation and climate change as do fossil fuel emissions. Demand for animal protein is projected to increase as its consumption (Tiseo et al., 2020). Currently, most of the world's fresh water and food are used for livestock farming (Dudgeon, 2019). To use resources judiciously and also protect the environment while feeding the populace, there is a need for alternative sources of protein.

To promote sustainable food production, it is critical to explore alternatives to animal nutrition. Another threat to global food security is organic waste such as leftover food and manure (Sniatala et al., 2023). In addition to producing methane, a greenhouse gas 25 times more potent than carbon dioxide (Black et al., 2021), it also contaminates water sources and transmits diseases (Rashmi et al., 2020). Strategies are needed to overcome these obstacles and enhance global food production. Entomophagy, which is the consumption of insects as a source of protein and nutrients, enables the development of sustainable food systems (Matandirotya et al., 2022). Numerous insect species are consumed on every continent (Anankware et al., 2021). Additionally, insects can be reared sustainably on organic waste materials with minimal environmental impact (Sangiorgio et al., 2021). They can be utilized in producing diverse products such as animal feed, fertilizer, and biodiesel (Fowles & Nansen, 2020). These expectations are based on the fact that biomass is already established as a source to produce clean fuels and/or petrochemical substitutes via pyrolysis. Biomass may be also converted chemically by hydrolysis to sugars, which may be fermented to give bioethanol (El–Shinnawy et al., 1983; Fahmy et al., 2017, 2020; Mobarak, 1983).

The larvae of the black soldier fly (BSFL), *Hermetia illucens* (L.) (Diptera: Stratiomyidae), are a promising alternative to conventional livestock fodder (Amrul et al., 2022). BSFL are rich in protein and fat and can be reared on a variety of organic wastes, such as culinary waste manure and agricultural residues (Surendra et al., 2020). In addition to having a low environmental impact, BSFL can be used to generate animal feed fertilizer and biofuel among other products (Singh & Kumari, 2019).

BSFL have several advantages over other insect species used in the protein and sustenance source. BSFL mature in as little as 21 days due to the rapid rate of development this makes them a more efficient protein source than insects like crickets and mealworms (Oonincx et al., 2019). Additionally, BSFL are simple to cultivate and can be grown in a variety of organic debris thus they are a more sustainable source of protein than traditional livestock which require a great deal of land and water (Gold et al., 2018).

The bioconversion rate of BSFL is the amount of protein and lipids they can produce from an allotted quantity of organic waste. The greater the bioconversion rate, the more effectively BSFL transform organic waste into valuable products (Siddiqui et al., 2022a, 2022b). The final product of BSF treatment includes both the larvae and the frass they generate. The larvae can be used as a source of protein and animal nutrition while the frass can be used as a soil amendment or fertilizer (Klammsteiner et al., 2020).

Several variables can influence the bioconversion rate and the final product of BSF treatment (van Rozen et al., 2023). These variables include the type of organic waste used, the environmental temperature and humidity, and the density of the larvae (Cheng et al., 2017). In order to make BSF a more efficient and sustainable source of nutrition, its conversion rate and final products must be increased and optimized, respectively. Controlling the temperature and humidity of the environment is one method of enhancing the bioconversion rate and the final product of BSF treatment (Salam et al., 2022). It is essential to also regulate the larva's density, as this will prevent them from becoming congested and agitated (Niu et al., 2022).

In this review, we explore and discuss strategies for enhancing the bioconversion rate and improving the end products derived from BSF treatment. The paper highlights the benefits of using BSFL compared to other interventions in the context of bioconversion processes. It also shows the significance of optimizing the bioconversion rate of BSF treatment and the potential products that can be derived from this technique.

2 Optimization products derived from black soldier fly larvae treatment

2.1 Black soldier fly role to overcome global food security issue

The formidable task of providing sustenance to a population of nine billion individuals by the year 2050 is one of the most significant obstacles of the current century (De Laurentiis et al., 2016). There exists a pressing need for a novel method to address food security which refrains from compromising biodiversity and ecosystem services, minimizes the effects on climate change, and shifts the emphasis from availability to accessibility and from caloric intake to nutrient content. This necessitates dismantling disciplinary barriers and striving for enhanced nutritional outcomes, while minimizing environmental harm (Foresight, 2011; Garnett, 2014; Godfray et al., 2010). These three pathways are essential for achieving the goal of feeding the world's growing population (De Laurentiis et al., 2016).

A significant amount of agricultural waste is generated on a daily basis in order to meet the demands of a growing population. It is crucial to manage this waste properly in order to ensure the sustainability of agriculture and to protect the availability of food and the health of humans. These wastes come from a variety of sources, including crop residue, agro-industries, livestock, and aquaculture. The primary components of this waste are cellulose, lignin, and hemicellulose. Currently, these agricultural wastes are either burned or buried in the soil, which leads to pollution and contributes to global warming. Traditionally, crop residues have been utilized in several ways, such as combustion, animal feed, roof thatching, composting, soil mulching, matchstick production, and paper manufacturing. However, lignocellulosic biomass can also be used as a sustainable source of biofuel and energy, which can help mitigate the shortage of fossil fuels and address the issue of climate change (Koul et al., 2022).

The phenomenon of climate change is expected to have significant and widespread effects on the production of crops, livestock, and fisheries, as well as on the prevalence of crop pests. However, current studies on the impacts of climate change on food systems focus primarily on crop yields, neglecting other important components and dimensions of food security. In order to effectively address the serious threats posed to food security by climate change, it is imperative that research efforts prioritize action-oriented approaches (Campbell et al., 2016).

The population's fast growth has led to a rise in the need for larger quantities of protein. Due to a deficit in protein sources from plant-based feeds and a ban on animal-based ones, the pursuit of alternative proteins has been necessary (Lu et al., 2022). Edible insects are an attractive option as a food source owing to their nutritional composition and minimal environmental impact. Numerous edible insects have substantial protein content comparable to that of animal protein, and they also contain all the essential amino acids (Bessa et al., 2020; Bukkens, 2005; Chakravorty et al., 2014). As the demand for insects as a food source rises, efforts persist to enhance the acceptance of insect-based goods in the Western hemisphere. BSFL, predominantly employed in animal feed, possesses considerable capacity to furnish a sustainable nutrient source for human consumption (Bessa et al., 2020). They are extensively studied and cultivated owing to their capability to convert waste materials into high-quality proteins, fats, and minerals. They possess gut enzymes that enable them to consume various substrates, thereby reducing agricultural waste by feeding on and converting them into nutritionally rich body mass (EFSA, 2015; Mertenat et al., 2019; Woods et al., 2019; Bessa et al., 2020).

The organic waste materials that may be present in the breeding of BSF include pharmaceuticals, pesticides used in agriculture, and harmful toxins such as dioxins, polyaromatic hydrocarbons, and so on. This emerging industry is therefore apprehensive about the potential transfer and buildup of these pollutants in the BSF's food chain (Rehman et al., 2023). The improper management of these biodegradable wastes poses a significant global threat in terms of the environment, society, and economy. The utilization of BSFL for waste treatment aligns with the principles of circular economy, as it allows for the conversion of such waste into valuable commodities. The by-product of this process, known as frass, is a residue that is regularly produced in waste management facilities and can be utilized as an organic fertilizer in agriculture. Despite this, numerous aspects related to frass remain unclear, including its nutrient and bioactive compound composition, post-processing requirements, behavior in soil, and impact on plant metabolism (Lopes et al., 2022).

2.2 Challenges and opportunities to get higher yield and quality of the end product

The enhancement of the economic worth of insect-derived products presents a promising avenue for promoting the utilization of insects as renewable, eco-friendly resources. However, the creation of insect-based bioproducts may encounter obstacles, such as inadequate market value and insufficient appeal for edible consumption. To address these challenges, the production of value-added products must be pursued (Nugroho et al., 2020). The usage of BSFL by corporations for creating value-added products has become more prevalent, although the information available on the economic aspects of organic waste bioconversion by BSFL is insufficient. Regulations for substrates used in insect farming are still in place due to a lack of evidence-based research and information; hence additional studies are necessary to evaluate potential food safety hazards (Bosch et al., 2019; Joly & Nikiema, 2019; Liu et al., 2022). The findings of some limited research indicate that BSFL can release mycotoxins and are capable of reducing the levels of pesticides and pharmaceuticals in the substrate, and microplastics and organic pollutants do not affect the growth parameters and composition of BSFL. On the contrary, BSFL were observed to accumulate specific heavy metals, when grown on spiked substrate. This information can aid in the development of regulations and processing methods to minimize these risks, providing a risk assessment framework for the commercialization of BSFL (Alagappan et al., 2022a, 2022b). The utilization of organic wastes like human feces, animal manure, and food waste would result in minimal global warming potential, energy consumption, and land requirements and incur minimal financial costs (Bosch et al., 2019; Joly & Nikiema, 2019; Liu et al., 2022).

A variety of organic waste materials could be consumed by BSFL during rearing, ultimately reducing the initial weight by half in a shorter time frame, compared to traditional composting methods. The core elements of the BSFL system include the larvero (a kind of tray) and fly house, and it is imperative to have a breeding center to ensure the well-being of adult and larval BSF. The BSF organic waste processing facility involves initial waste preparation, biowaste treatment utilizing BSFL, segregation of BSFL from remaining process residue, and the processing of larvae and residue into salable commodities (Amrul et al., 2022). The rearing of *H. illucens* in temperate regions necessitates the implementation of artificial techniques to ensure the consistent production of superior quality eggs and larvae, but limited research has been conducted on the intricate processes of mating and oviposition that govern the reproduction of *H. illucens*. Studies carried out under semi-artificial rearing conditions have revealed that the frequency of mating fluctuates according to the season, with speculation that this behavior may be attributed to the varying intensity of sunlight resulting from seasonal changes (Hoc et al., 2019).

The nutritional composition of the substrate is very important because nutrients affect the growth of BSFL. Moreover, substrates with high levels of lignin and cellulose (like dairy manure) have demonstrated low digestibility by BSFL. Research indicates that pretreatment methods can enhance the substrate's digestibility and biodegradability by BSFL (Peguero et al., 2022). The nutritional quality of larval feeding substrates can be developed by incorporating nutrient-dense materials such as soybean curd residue or chicken manure, and the process of microbial fermentation can be utilized for breaking down the waste of lignocellulosic materials and release nutrients required by BSFL (Rehman et al., 2023). Also, the performance of BSFL is influenced by a crucial balance between moisture content and the nutritional composition of waste. Although higher moisture content facilitates faster growth of BSFL, this phenomenon is only applicable within a specific range of moisture content values, which varies according to the nature of the waste stream in question (Cheng et al., 2017; Palma et al., 2018; Purkayastha & Sarkar, 2022; Siddiqui et al., 2022a, 2022b).

To sum up, it is recommended to examine Table 1 which presents more information about BSF production and optimization, for understanding all effective factors and parameters to obtain a high-quality BSF product.

2.3 Nutritional aspects of products derived from black soldier fly

Products derived from BSFL and BSF protein powder have gained attention in recent years, due to their potential as a sustainable and nutrient-rich food source (high protein

Table 1 Overview of studies from 2009 to 2023 about optimization of BSF production

Year	Objectives	Key findings	Reference
2009	To investigate life history characteristics of BSF at different temperatures, and to explore the correlation between developmental features during immature phase	Small variations in temperature, as little as 3 °C, can result in notable compromises in biological fitness of both male and female organisms, which in turn affect their life history traits	Tomberlin et al., (2009)
2012	To establish relative humidity thresholds that affect the hatching of BSF eggs and emergence of adult organisms	The success of egg eclosion and adult emergence is observed to be positively correlated with increasing levels of relative humidity, while the duration of development tends to decrease with rising levels of relative humidity	Holmes et al., (2012)
2014	To assess the impact of a low-water artificial diet on growth and developmental patterns of BSF	BSFs cannot grow and develop properly, if their food has less than 70 water content	Yu et al., (2014)
2015	To ascertain the proficiency of BSF as a bioconversion agent for customary food waste generated by Indonesian restaurants	The rate of BSFL growth fed on organic wastes is markedly improved. The rate of waste conversion is heightened, when the waste is reduced in size before being introduced to larvae, which are not isolated from other agents of bioconversion	Putra et al., (2015)
2017	To investigate whether photophase duration influences the growth of immature BSF	The duration of light exposure on the growth and development of young organisms is the most significant during the stage following feeding, while it is relatively less impactful during the pupal stage	Holmes et al., (2017)
2018	To devise a suitable agricultural approach and comprehend the effects of diverse nourishment sources (vegetable wastes, horse manure and tofu dreg) on cultivation of BSF	All materials can be used as feed, but their physical and chemical properties impact the development time, efficiency of digestion and biomass production	Kinasih et al., (2018)
2018	To assess the influence of substrate pH and feeding regimes on biological processes of BSFL, pre-pupae, as well as adults	The assessment of a suitable feeding mechanism and initial pH level of substrate are critical factors that can contribute to a reduction in time and an increase in weight during the production of larvae	Meneguz et al., (2018a, 2018b)
2018	To investigate variances in chosen oviposition characteristics and the duration of male and female adult BSF's lifespan in the presence of three distinct artificial light sources	Light-emitting diodes are recommended for small-scale rearing	Heussler et al., (2018)
2018	To assess the developmental time, survival rate, weight, etc. of adult BSF, when raised on spent grains with or without brewer's yeast supplementation	The findings hold significant value in terms of facilitating the refinement of commercial mass rearing protocols for BSF, taking into consideration diverse environmental factors and forecasting population dynamics patterns through the utilization of simulation models	Chia et al., (2018b)

Table 1 (continued)

Year	Objectives	Key findings	Reference
2019	To determine whether BSFL are able to be produced by using horse manure and cull potatoes, compared to waste of restaurants, and	The utilization of BSFL shows immense potential as a technology for efficient recycling of organic wastes, encompassing those which originate from plant sources	Alyokhin et al., (2019)
2019	To evaluate the impact of sex ratio, population density, and diurnal cycle on reproductive behavior of *H. illucens* in controlled environment	An efficient breeding unit should be maintained under a 6 h/18 h (light/dark) photoperiod by using a progenitor population dominated by females with a minimum density of 6500 individuals per cubic meter	Hoc et al., (2019)
2020	To ascertain the usefulness of bacterial addition in breeding and industrialization of BSFL and to determine growth, gut microbiome composition and waste conversion	The utilization of identified bacterial supplements and manipulation of BSFL system could expand its ability to decompose stubborn substances. Additionally, this approach has potential to be useful in bioremediation efforts and enhance the production of valuable proteins and lipids	Kooienga et al., (2020)
2020	To formulate a model with the aim of accurately describing fluctuations in dry mass that occur during developmental stages of larvae and their transitions	The proficiently designed models, equipped with the estimated parameters, exhibited exceptional performance, thereby demonstrating their viability in decision-making support systems and automation for extensive production operations	Padmanabha et al., (2020)
2020	To assess certain life history characteristics of BSF that has been fed with either dairy, swine or poultry manure	The type of manure does not affect the weight of insects, before they turn into pupae. However, insects that are given dairy manure took longer to develop into pupae and fewer survived to that stage compared to those given poultry or swine manure	Miranda et al., (2020)
2020	To evaluate the combined impact of three distinct light sources and three types of nutrients on production metrics of BSF, with specific emphasis on the performance of adult specimens	The production parameters are primarily affected by nutrition, with light factor having a secondary impact. Inclusion of sugar in diet has a beneficial effect on egg production, leading to an extended oviposition period and increased lifespan of adult individuals	Macavei et al., (2020)
2020	To examine the cultivation of maggot BSF, utilizing tofu waste media supplemented with varying levels of chicken feces	The utilization of chicken excrement as a medium for BSFL with varying levels has a noteworthy impact on dry matter, crude fat, protein and fiber composition of larvae	Mahmud et al., (2020)

Table 1 (continued)

Year	Objectives	Key findings	Reference
2021	To suggest a suitable apparatus for the cultivation of BSFL, identify the most favorable conditions for their reproduction and growth in the local environment, and to achieve cost-effective production of insect meal	The suggested technological advancements can provide the means for farmers in animal sector to breed BSFL effortlessly	Gougbedji et al., (2021)
2021	To establish a growth model for BSFL to elucidate its production using fruit and vegetable wastes	The utilization of growth model may prove beneficial in computation of scale-up measurements	Prasetya et al., (2021)
2021	To ascertain the ideal temperature for achieving maximum production and reproduction of BSF	The temperature has a significant impact on growth and reproduction of BSF, and can influence various aspects of biological life cycle of insect, including survival during immaturity, growth, gender ratio and so on	Hosseini and Arast, (2021)
2021	To capture the development and metabolic abilities of BSFL under varying substrate moisture levels, including their rates of food absorption, growth and CO_2 output, as well as the expenses of overall growth and upkeep efficiency	The metabolic efficiency of BSFL exhibited little sensitivity to variations in substrate moisture content, which indirectly impacted their performance by influencing the microbial processes that co-occur in the substrate	Bekker et al., (2021)
2021	To ascertain whether the incorporation of *Rhodococcus rhodochrous* in diet of BSFL would yield expedited larval development, amplified final larval body dimensions and enhanced conversion efficacy	Despite encouraging outcomes regarding the integration of *R. rhodochrous* into the dietary regimen of BSFL, further investigation is required to determine the optimal dosage for industrial applications	Franks et al., (2021)
2021	To examine the impact of adult density, light exposure and their interaction effect on certain life history traits of BSF	Survival rate of insect, first oviposition peak and averaged reproductive output of individual female are affected by exposure of light × adult density; however their individual effects are insignificant	Liu et al., (2022)
2022	To determine the impact of environmental conditions (humidity, pH, sunlight, temperature and moisture content) on development and growth of BSFL	The growth and development of BSFL are greatly influenced by alterations in environmental conditions. Optimal temperatures for BSFL growth fall within the range of 27 to 35 °C, while humidity levels of 70 to 75 are ideal. Furthermore, the light-sensitive nature of BSFL necessitates the provision of dark ambient conditions	Salam et al., (2022)

Table 1 (continued)

Year	Objectives	Key findings	Reference
2022	To record the utilization of waste from previously edible products for BSFL under extended periods of time in semi-industrial settings, and to evaluate the output of BSFL feed generated from former foodstuff enriched with various waste streams and raised at varying stocking densities	Recycling of nutrients from former foodstuffs is a safe and successful process that can be utilized in production of BSFL	Gligorescu et al., (2022)
2022	To evaluate kitchen, vegetable, fruit, rice moth rearing and fish slaughter wastes for multiplication potential of BSF	The capacity of BSFL to decompose kitchen and rice moth rearing has potential for enhancing the biomass production of this detritivore insect through the implementation of appropriate development parameters	Yandigeri et al., (2022)
2022	To determine how survival and population rates, larval and adult weights, as well as development time are impacted by different organic substrates, specifically a blend of wheat bran, soy, and corn meal, a mixture of fruits and vegetables, and dairy manure	The growth of BSF is observed to be comparatively lower in treatment of dairy manure	Singh et al., (2022)
2023	To specify the potential beneficial impact of altering air temperatures during specific stages of larval growth	Consideration of population size, larval density and air temperature are crucial for BSF mass production, because they greatly affect overall larval yield	Li et al., (2023)
2023	To scrutinize the development of BSFL nourished on wheat bran subjected to ethanol-extracted honeybee propolis	The inclusion of propolis in wheat bran was found to have a positive impact on growth performance of BSFL	Bakaaki et al., (2023)

BSF black soldier fly, *BSFL* black soldier fly larvae and fat contents, amino acid profile). Getting flour from insects is one approach to start including edible insects in their diet or using them to make new recipes. For a variety of reasons, these flours could be utilized as a product for food fortification and offer high levels of protein and mineral (Ca, P, Cu, Fe, Mg, Mn, K, etc.) contents and antioxidant qualities. This protein also has a high level of digestibility and a high-quality amino acid profile (Botella–Martínez et al., 2021). The BSF's protein portion is similar to soybean meal and primarily made up of amino acids. Moreover, BSFL exhibit crude protein content that is on par with or slightly higher than various plant-based proteins, including linseed, sunflower, cottonseed, lupins, or faba beans, as reported by both De Marco et al. (2015) and St–Hilaire et al. (2007). The amino acid composition of BSF is comparable to high-quality animal and vegetable proteins such as egg white and soybean, while also containing elevated levels of tyrosine, phenylalanine, and histidine in comparison with these protein sources, according to Caligiani et al. (2018).

The BSFL has high amount of lauric, oleic, myristic, palmitic and palmitoleic acids (Caligiani et al., 2018). Lauric acid, one of the primary ingredients in coconut oil, makes up the majority of the BSF's oil portion (Bakker, 2020). The unsaturated fatty acid content of BSFL is low (19–37%). Compared to fish oil, BSFL have lower concentrations of EPA (eicosapentaenoic acid 20:5n–3) and DHA (docosahexaenoic acid 22:6n–3) and higher concentrations of polyunsaturated fatty acids (PUFA) (Hawkey et al., 2021; van Huis et al., 2020).

Enzymes, chitins, antimicrobial peptides, excretions, organic waste residues, and BSF skins are released during the process of extracting the oil and protein from the BSF (Bakker, 2020). The extraction of fats and purification of proteins in insect meals present challenges in terms of their environmental sustainability, labor requirements, and added expenses. These operations can have a negative impact on the financial viability of using insect meals. Moreover, the use of high temperatures during these processes can potentially lead to the degradation of amino acids and antimicrobial proteins, and defatting may result in an increase in the proportion of chitin in the meal. When present in excessive amounts, chitin can be considered an anti-nutritional factor that reduces the digestibility of nutrients, thereby diminishing the overall nutritive and functional value of insect meals. Furthermore, the beneficial characteristics of the fatty acid composition, such as a high content of lauric acid, are also diminished by the separation of fats from insect meals (Caimi et al., 2020; Rawski et al., 2020).

As a consequence, it is worth noting that the exact nutritional composition of BSFL and BSFL-derived products may vary depending on the feed of BSFL which was raised on and the used processing methods, although, in general, BSFL and their derived products (feed and food) are considered highly nutritious due to the high protein content of BSFL, sustainable, and environmentally friendly.

2.4 The risk of contaminants on larval diet

In the European insect industry, BSFLs are commonly raised using plant-based feeding materials. These include vegetable and fruit waste, wheat bran, grass, brewery waste, hay, and plant-derived powders. Additionally, approved feed materials for food-producing animals, such as marine macroalgae or seaweed, can also be utilized as resources for feeding BSFL. While BSFL are generally recognized as effective bioconverters, there are certain risks associated with potential contaminants present in their diet. These contaminants can include chemical substances like pesticides, heavy metals, and antibiotics, as well as environmental pollutants and microbial pathogens such as *Salmonella* and *Escherichia coli* (Fig. 1). It is important to mitigate these risks and ensure the safety of the final products derived from BSFL.

Ensuring safety is crucial when considering the use of insects as feed. The presence of chemical hazards in insects and insect materials, as well as the potential transfer of undesirable substances from the feeding media to the insects, is important factors that need to be addressed. The European Food Safety Authority (EFSA) has identified significant knowledge gaps in this area, emphasizing the need for further research and understanding of these risks (EFSA, 2015). In the case of using seaweed-enriched media for rearing insect larvae, it is also essential to evaluate the feed and food safety aspects. Specifically, a better understanding of the presence of heavy metals in processed insect products like insect meal and insect lipids, as well as their potential transfer to farmed animals, is necessary (Biancarosa et al., 2018). This knowledge is crucial for conducting thorough safety assessments and ensuring the suitability of insects and their products for food and feed purposes. To address these concerns and ensure the safety of BSFL as feed/food, various regulations and guidelines may be in place in different countries or regions. Producers need to adhere to these regulations, conduct regular testing for contaminants, and employ quality control measures throughout the production process to minimize the risks associated with potential contaminants in the larvae's diet.

2.4.1 Microbial pathogen

BSFL has gained significant attention in recent years as a sustainable and alternative protein/oil source for animal feed and human consumption. However, it is crucial to assess the potential microbial pathogen risks associated with BSFL and its derived products. Due to its nature, BSFL can be effectively grown on sludge and various wastes (food industry, slaughterhouse, human or animal manure, etc.). The abundance of microorganisms found in the BSFL can vary due to the wide range of feeding substrates available, leading to a diverse microbial load (Gold et al., 2018; Wynants et al., 2019). In some countries, such as Canada, BSFL is produced on food industry waste such as fruits and vegetables to reduce or prevent pathogen growth. The likelihood of coming into contact with microbiological pathogens in the end product is significantly elevated due to the potential presence of substantial microbial populations in the organic residue. This is compounded by the fact that the larvae excrete their feces within the environment, where they mature and are processed as intact larvae, including their digestive tracts (De Smet et al., 2018; Gold et al., 2018; Wynants et al, 2019). The duration of feed withdrawal is important to allow the gastrointestinal tract to clear. However, one study has shown that this procedure does not improve larval microbial load (Larouche, 2019) and may alter the gut microbiome (Yang et al., 2021).

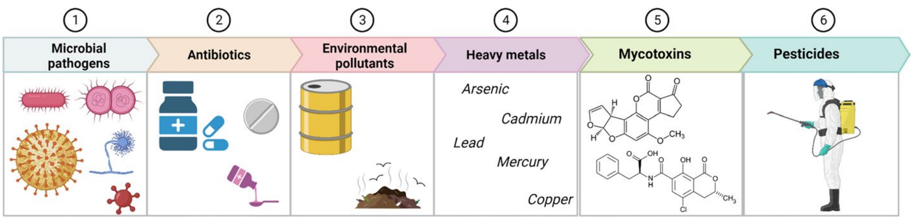

Fig. 1 Risk of contaminants on larval diet (created with Biorender.com)

Any foodborne pathogens present in the substrate have the potential to be transmitted to the intestinal tract of BSFL, which can subsequently lead to illnesses in both conventional farm animals fed with BSF-based feed and individuals who consume animal products derived from them (Čičková et al., 2015; Erickson et al., 2004). BSFL that have had minimal processing are extremely contaminated and must be thermally treated or otherwise decontaminated. The pathogens such as *E. coli, B. cereus, Salmonella* spp., and *Clostridium* spp. have been found in BSFL, which could pose a health concern if consumed (Gold et al., 2018; Larouche et al., 2019; Wynants et al., 2019). It can be stated that it is crucial to implement stringent quality control measures and regularly test the feeding media for pathogens when rearing BSFL. Also, preserving dead BSFL poses a significant challenge, because of their elevated moisture content (78–84%), neutral pH (6–9), and substantial microbial presence. To ensure optimal preservation of BSFL, it is essential to incorporate decontamination and processing techniques (heat application, freezing, etc.) that effectively minimize contamination and inhibit microbial proliferation (Larouche et al., 2019; Wynants et al., 2019). Contrarily, numerous studies have demonstrated that BSFL exhibits antimicrobial properties, and can decrease the presence of pathogenic bacteria like *Salmonella* and *E. coli* in the materials they consume (Čičková et al., 2015; Erickson et al., 2004; Lalender et al., 2015; Nguyen et al., 2015).

2.4.2 Residual pesticide

Ensuring the chemical safety of BSFL as a feed ingredient necessitates guaranteeing the composition of their rearing substrate, as it has the potential to pose safety risks by facilitating the bioaccumulation of diverse (in organic compounds, including heavy metals, mycotoxins, pesticides insecticides, herbicides, etc.), and more, within the BSFL (Lievens et al., 2021). The researchers' findings indicated that BSFLs do not accumulate pesticides (chlorpyrifos, chlorpyrifos-methyl, pirimiphos-methyl, azoxystrobin, and propiconazole) in their tissue. In addition, pesticides do not affect the growth of BSF (Purschke et al., 2017; Wang et al., 2017). In a study, newly hatched BSFL were fed with a corn-based substrate that was contaminated with heavy metals, mycotoxins (including aflatoxins B1/B2/G2, deoxynivalenol, ochratoxin A, zearalenone), and pesticides (like chlorpyrifos, chlorpyrifos-methyl, pirimiphos-methyl) under specific breeding conditions (10 days, 28 °C, 67% RH). According to the researchers' findings, there was no evidence of mycotoxin or pesticide accumulation in larval tissue, and these substances did not have a significant impact on the growth determinants compared to the control group (Purschke et al., 2017).

2.4.3 Heavy metals

While the nutritional composition of BSFL can be regulated through their feeding, it is important to consider the potential accumulation of heavy metals and toxins, when using insects as animal feed. Growing insects on contaminated substrates may lead to the accumulation of harmful substances, posing a potential risk. Therefore, it is crucial to address this concern and ensure the safety of insects used as feed (da Silva & Hesselberg, 2020; Raksasat et al., 2020; Surendra et al., 2016). The levels of heavy metals and arsenic in insects vary depending on the species of organism, growth stage, and features of the elements and their concentrations in the substrates (EFSA, 2015). Cd, Pb, Hg, and metalloids are substances that carry significant chemical risks, particularly in terms of their impact on the environment. Insects have been effectively utilized as bioindicators for assessing environmental pollution and heavy metal contamination due to their ability to absorb and accumulate metals. Thus, it is crucial to examine the concentrations of these compounds in the feeding substrates currently employed for rearing agricultural insects. Because heavy metal-contaminated substrates are fed to BSFs, heavy metal accumulates in BSFL as a result (Azam et al., 2015; Biancarosa et al., 2018). In conducted research, newly hatched BSFL were provided with a corn-based substrate intentionally contaminated with heavy metals (arsenic, cadmium, chromium, mercury, nickel, and lead), mycotoxins, and pesticides under specific breeding conditions (10 days, 28 °C, 67% relative humidity). The presence of heavy metals in the substrate had a negative impact on the growth of the larvae, leading to significantly lower post-trial larval mass and feed conversion ratio. Cd and Pb were found to accumulate in larvae with accumulation factors of 9 and 2, respectively, while the concentrations of other heavy metals remained below the initial substrate levels. Based on these findings, the researchers emphasized the importance of monitoring contaminants, particularly Cd and Pb, in both the substrates and feed containing BSFL used for livestock feed, to ensure the safety of feed and food along the entire value chain (Purschke et al., 2017).

2.4.4 Mycotoxin

Mycotoxins represent a wide range of fungal metabolic by-products that possess varied levels of toxicity to both animals and humans (Tola & Kebede, 2016). The potential presence of mycotoxins in BSFL and derived products raises concerns about their safety for human and animal consumption. However, Wang et al. (2017) and Purschke et al. (2017) reported that BSFL do not absorb mycotoxins from the feeding media, and the mycotoxins do not accumulate in the larval tissue. To date, studies have indicated that the growth performance and survival rate of BSFL are not affected by exposure to mycotoxins such as aflatoxins B1, B2, and G2, ochratoxin A, fumonisin B1, and B2, zearalenone and zearalenone mycotoxins. This is likely attributed to the limited accumulation of these various mycotoxins, as reported by Leni et al. (2019), Purschke et al. (2017), and Bosch et al. (2017). Based on the studies, it appears that BSFL can effectively transform contaminated substrates containing levels of mycotoxins and/or pesticides that surpass the permissible limits into insect biomass suitable for feed or non-food applications, all while preventing the transmission of such contaminants within the feed chain. (Purschke et al., 2017).

2.5 Challenges and opportunities about black soldier fly

In the market, edible insects have traditionally been available in dried, powdered, and/or flour forms. Vendors offer various packaging options, including bulk quantities, powdered or flour products, snacks, candy, chocolate-covered varieties, and even infused liquors. Furthermore, researchers have recognized, insects as potential food ingredients for sports nutrition supplements, such as protein concentrates/isolates, flours, energy bars, protein shakes, and hydrolysates, due to their high protein content and balanced amino acid profile (Melgar–Lalanne et al., 2019).

BSFL can be considered a functional and safe food ingredient (Beessa et al., 2023), and it can be powdered, dried, cut, and eaten alive (Iñaki et al., 2022). The treatment of BSFL can be used in a variety of potential products, such as animal feed, pet food, human food, organic fertilizer, and biodiesel across different industries like food, pharmaceuticals, nutraceuticals, waste treatment, biofuel, and so on.

BSFL are currently cultivated and utilized as animal feed, taking into account the specific regulatory requirements within each region. However, in terms of commercial utilization in human food, there is a possibility to process BSFL into a textured protein with a distinctive flavor. One significant advantage of BSFL over other insects is their remarkable ability to convert waste into food, creating value and facilitating the closure of nutrient cycles, while also reducing pollution and associated costs. Despite feeding on waste, contaminated feed, and manure, BSFL cannot transmit parasites or illnesses, when utilized in feed. The inherent advantage of BSFL in waste conversion also presents a significant drawback, as it is accompanied by social stigmas and legal restrictions on consuming organisms that feed on garbage. These existing taboos surrounding the consumption of insects further compound the challenges associated with embracing BSFL as a viable food source (van Huis et al., 2020; Wang & Shelomi, 2017).

The insects that are connected to manure and organic waste can be crucial for the sustainable valorization of organic waste streams as high-value products or feed. In this context, the BSFL are of great importance, because they can transform a variety of residual organic materials into protein-rich biomass suitable for use as components in pig, poultry, and fish feeds and pet foods (De Marco et al., 2015; Maulu et al., 2022; Pastor et al., 2015). There is a lot of promise for the BSFL, which is primarily used as animal feed, for use as a reliable source of nutrients for human meals (Bessa et al., 2020; Bosch et al., 2014).

In general, the nutritional composition of the product, digestibility, shelf life, etc. may be impacted by insect-rearing methods and conditions and protein and biomass processing techniques (Maulu et al., 2022). The protein content of the insect meal can be increased by defatting, while rearing the insects on a substrate high in n-3 polyunsaturated fatty acids may have resulted in higher polyunsaturated fatty acid (PUFA) content in the insects (Alfiko et al., 2022; Zarantoniello et al., 2020).

According to an AAFCO study from January 19, 2016, the FDA in the USA permits whole-dried BSFL as feed for salmonids. Three states—Idaho, Indiana, and Alaska—go even further permit the BSFL as feed for all species. Additionally, the FDA has not yet approved the use of dried BSFL in chicken broiler/layer feed for 2018. Numerous BSF breeding enterprises worldwide are expanding and improving production in response to the potential for BSF and the emergence of new markets. Due to these advancements, BSF was recognized as an insect for industrial rearing and granted the status of a farm animal under European law (EG no. 1069/2009) (De Smet et al., 2018; Van Huis et al., 2015). BSF is regarded as symbiotic, since it can reproduce without harming humans (Menino & Murta, 2021).

Although there are many studies on the use of BSFL as an additive to animal feeds, studies on human consumption are limited. BSFL was added to Vienna-style emulsified sausages at 0% (control, produced by pork), 28%, 31%, and 34%, and it was observed that the sausages with BSFL were similar to those produced with pork in terms of ash and fat content, firmness, and stickiness, but lower in terms of protein and moisture content and chewiness. Regarding protein and ash contents, hardness, cohesiveness, and gumminess, the 28% BSFL addition was most similar to the control sample, demonstrating the potential of BSFL for partial use in emulsified meat products (Bessa et al., 2019). The addition of BSF pre-pupae to the semi-whole wheat flour (0% (control), 2%, and 4% by weight) resulted in lower moisture content, falling number, dough extensibility, foaming capacity and higher gluten, protein, ash, free and total amino acids contents, tenacity, rheological properties (F max and ε break). No statistical differences were observed between the dough and bread that were prepared with semi-whole wheat flour, and BSF pre-pupae-enriched semi-whole wheat flour in terms of height, weight, and dry residue. The BSF pre-pupae-enriched bread is rich in essential amino acids, compared to the control (Montevecchi et al., 2021).

The addition of BSFL to meat products may cause texture problems due to the lack of meat proteins. In addition, an additive such as lecithin or carrageenan can be added to obtain a stable emulsion with BSFL in meat products, such as sausages (Bessa et al., 2019). The BSF pre-pupae addition increased the gluten content of flours. For this reason, it can be stated that BSF may contain water-insoluble proteins, such as glutenin and prolamin (Caligiani et al., 2018; Montevecchi et al., 2021). According to Murefu et al. (2019), food manufacturing techniques like baking, boiling, frying, and roasting are known to improve the safety, and consequently, the acceptance of insect-based foods. Therefore, BSFL can be added to bakery products (bread, crackers, cookies, etc.), pasta, instant powder soup, etc. formulations in powder form, taking into account safety issues. The impact of BSFL on the fatty acid profile of the resulting meat, which increases the quantity of saturated and monounsaturated fats and/or decreases the percentage of polyunsaturated fats, is one of the main concerns with their use in meat products, despite how simple it is to consume and include them (Iñaki et al., 2022). An overview of challenges and opportunities as solutions of products derived from BSF treatment are given in Table 2.

The challenges to be addressed in making BSFL a feasible food choice encompass issues related to safety, technofunctional characteristics, nutritional considerations, consumer perceptions, and the various potential uses of BSFL in food products. At present, the recommendation is to utilize a cleaner waste stream, like spent grains and pre-consumer vegetable matter as suggested by (EFSA, 2015), when producing BSFL intended for human consumption. This approach is aimed at mitigating risks and standardizing the process. Nevertheless, the possibility of introducing alternative waste streams into their diet may be explored, contingent upon ensuring food safety. However, it is crucial to emphasize that additional validation studies are needed to gain a comprehensive understanding of the safety aspects associated with rearing BSFL intended for human consumption on various waste streams (Bessa et al., 2020).

2.6 Environmental impact

In the context of food crises and sustainability in relation to climate change, additional environmental measures are needed. Livestock provide 25% of total dietary protein and contribute to a variety of critical global challenges, including greenhouse gas emissions as well as freshwater, fossil fuel, and land consumption. Ruminants in particular are known to produce methane, a greenhouse gas with a global warming potential 20 times greater than carbon dioxide. In order to minimize the negative impacts of livestock on the environment and for the sustainability of human nutrition, the search for alternative edible foods and nutrients such as edible insects (BSF, etc.), in vitro meat is gaining momentum. The conviction that conventional meat supplies will be insufficient to satisfy the demand for protein in the future has prompted consumers to seek alternatives that resemble meat. These factors have collectively sparked growing curiosity in utilizing insects as a protein source. According to unbiased market analysts, the worldwide insect market is projected to reach a value ranging from $722.9 million to $1.2 billion by 2023. In vitro meat production is reported to consume 7–45% less energy, use 99% less land and 96% less water, and emit 78–96% less greenhouse gas emissions compared to conventional meat production (Post, 2014; Herrero et al., 2016; de Castro et al., 2018; Meticulous Research, 2018; Persistence Market Research, 2018).

Table 2 Overview of challenges and opportunities as solutions of products derived from BSF treatment

No	Challenges	Opportunities as Solution	Reference
1	Political		Raman et al., 2022
	To convince the government for using the BSFL for food and/or feed	Higher demand and interest in BSFL industries	
	Unable to categorize the land	Establish BSFL production	
2	Economic		Raman et al., (2022)
	Higher production and operational costs for the production of BSFL	Build a cost-effective BSFL production system and governmental funding	
	The high price of BSFL	Reasonable pricing	
	Constant BSFL supply	Provide environmental sustainability	
3	Institution and legal		Raman et al., (2022)
	Needs documentation	Standardizing the regulations and processes	
	No Halal certification	Introducing Halal certification to standardize	
	Needs guidelines for specific conditions (bad smell in rearing area)	Conducting regular inspections	
4	Social and Cultural		Raman et al., (2022)
	Public concerns (hygiene and smelling in the rearing area)	Showing the rearing areas by visiting programs	
	The negative perception of BSFL (unpleasant insect)	Training& education & awareness programs	
5	Composition of the feed (Wastes as a substrate)		Fu et al., (2022); Raman et al., (2022)
	Provide constant BSFL nutritional quality	Use a supply of consistently similar resource material (Partnering, optimization, and research)	
	Growing on the feces	The religious perspectives have to be taken care of (Halal compliance)	
	Needs constant and sufficient organic waste	Partnering and research	
	Needs financial resources for researchers	Funding opportunities	
6	Microbial risks	Strongly depends on the feed medium	EFSA, (2015)
7	Allergen risks (anaphylactic shock in some cases)	The presence of the insect proteins and the potential allergenicity have to be mentioned in the label	EFSA, (2015)
8	Heavy metal and arsenic accumulation (environmental contaminants, cadmium, lead, mercury, etc.)	The feed medium should be analyzed and BSF has to be fed with heavy metal-free feeds	EFSA, (2015)
9	Mycotoxin accumulation	Controlling the levels of contaminants in the substrate The feed medium should be analyzed and BSF has to be fed with mycotoxin-free feeds	EFSA, (2015)

Table 2 (continued)

No	Challenges	Opportunities as Solution	Reference
10	Knowledge		Raman et al., (2022)
	Researches Workers (skilled expertise)	Courses in the universities Training & education	
11	Pesticide residues	The feed medium should be analyzed and BSF has to be fed with pesticide-free feeds	EFSA, (2015)

There is a scarcity of research on greenhouse gas emissions related to BSFL rearing and bioconversion activities (Boakye–Yiadom et al., 2022). The carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) emission of BSFL strongly depend on the different substrates (chicken feed, food waste, kitchen waste, pig manure, orange peel, broccoli and cauliflower trimmings, etc.) ranged between 1.17 and 344 kg/kg dry matter (dm) of BSFL, 5.5 and 10.066 mg/kg dm BSFL, 0.33 and 1904 mg/kg dm BSFL, and 0.00 and 125.27 mg/kg dm BSFL, respectively (Chen et al., 2019; Ermolaev et al., 2019; Guo et al., 2021; Lindberg et al., 2022; Mertenat et al., 2019; Pang et al., 2020; Parodi et al., 2021). A life cycle assessment was conducted on a structured pilot plant for BSF using multiseason data, as described by Smetana et al. (2019). The findings indicated that when compared to numerous traditional organic fertilizers and protein sources derived from animals or plants, both the production of fertilizer and insects had a favorable environmental impact. It was also reported that the primary source of emissions in the treatment of BSFL is the post-treatment of the residues (Guo et al., 2021). Crucially, a recent research study conducted by Mertenat et al. (2019) has revealed that treating kitchen waste with BSFL leads to a reduction in CH_4 and N_2O emissions when compared to the composting method. Consequently, BSFL emerges as an eco-friendly and efficient approach for managing organic waste, offering significant resource conservation benefits (Mertenat et al., 2019). It can be suggested that further investigation is required to establish the most environmentally friendly approach for managing these treatment residues.

In addition, there are multiple ways in which BSFL could positively impact the environment in a general sense and carbon emissions specifically. To begin with, BSFL that are harvested and preserved can temporarily store carbon that would otherwise be released into the atmosphere due to microbial decomposition. Furthermore, the production of food has a significant environmental cost, with agriculture being the major source of greenhouse gas emissions in the food system, contributing up to 12,000 million tons of CO_2 equivalent annually. By directly converting food waste into edible proteins and oils that can be utilized by animals or humans, BSFL have the potential to decrease the primary agricultural production of greenhouse gases (Gilbert, 2012; Werednia et al., 2017).

2.7 The market potential of BSF products

The market potential of BSF products such as protein or fat extract, chitin or chitosan source, powder/BSF flour, and fertilizer is rapidly gaining attention. Because, in addition to the previously mentioned nutritional composition, BSF are noninvasive, non-biting, non-pest fly species that support several potentially profitable sustainable products. The amino acid composition of BSF is comparable to high-quality animal and vegetable proteins, like egg whites and soybeans. Also, it contains elevated levels of tyrosine, phenylalanine, and histidine in comparison with animal and vegetable proteins. The high concentration of polyunsaturated fatty acids (lauric, oleic, myristic, palmitic, and palmitoleic acids) makes it a health-promoting oil source. BSF frass can be regarded as an effective organic fertilizer as well, due to its mineral content (N, P, K, Zn, Cu, etc.). For those reasons, it has a high market potential for protein and/or oil sources. It can be used as an animal feed/pet food or a protein or oil extract can be added to the animal feed/ pet food composition. Besides that, BSF frass can be sold as a valuable organic fertilizer. Although BSFL products have not been approved for use in human foods, BSF has been permitted for utilize as animal feed, aquaculture, and fertilizer taking into account the specific regulatory requirements within each region. Several companies such as EnviroFlight® (https://www.enviroflight.net/), The

Critter Depot (https://www.thecritterdepot.com/products/black-soldier-fly-larvae-frass), Innovafeed (https://innovafeed.com/en/accueil-anglais/), Nutrition Technologies® (https://www.nutrition-technologies.com/hi-frass), Entofood (https://www.entofood.com/) and so on, sell various BSF products such as fertilizer, animal feed and fish feed. The market potential for goods involving BSF can be increased significantly over the next few years (Caligiani et al., 2018; Dempster et al., 2022; Hawkey et al., 2021; van Huis et al., 2020).

Farming and the development of products derived from BSF offer promising opportunities in the food and feed industry, especially in terms of sustainability and circular economy practices. To create a sustainable and competitive market for BSF-derived products, it is essential to focus on both economic viability and scalability (cost efficiency and profitability, reliable and low-cost feedstock, production efficiency, etc.) while keeping environmental (sustainability and environmental benefits such as reducing the organic wates) and regulatory considerations (compliance with local and international regulation) in mind. Continuous improvement and adaptation to market dynamics will be crucial for success in this emerging industry.

2.8 Consumer acceptance and the future of products derived from black soldier fly treatment

Consumer acceptance plays a crucial role in shaping the future of products derived from BSF treatment. BSFL has gained attention as a sustainable alternative for various applications, such as animal feed, protein, oil, and /or chitin sources, and even direct human consumption. Sustainability, nutritional value, taste, texture, safety, regulations, education, and awareness can be accepted as key factors that influence consumer acceptance of BSFL.

Today, BSFL is grown and used as animal feed and fertilizer, taking into account the legal regulations in the region where it is produced. The use of BSFL as animal feed for some species is regionally permitted (De Smet et al., 2018; Van Huis et al., 2015). Additionally, EnviroFlight® (https://www.enviroflight.net/), The Critter Depot (https://www.thecritterdepot.com/products/black-soldier-fly-larvae-frass), Innovafeed (https://www.thecritterdepot.com/products/black-soldier-fly-larvae-frass) Many companies such as innovafeed.com/en/accueil-anglais/), Nutrition Technologies® (https://www.nutrition-technologies.com/hi-frass), Entofood (https://www.entofood.com/) sell BSFL products. In a study, American consumers' perceptions of the use of BSFL in animal feed and human consumption were examined, and it was observed that participants were much more willing to consume insect-fed animals than to directly eat insects. It was concluded that the insect diet significantly affects consumer acceptance, the BSFL fed with feces is not acceptable, insect-fed birds and chickens are more acceptable than fish and animals, and participants are willing to feed their dogs with insect-containing feed. It was also concluded that the use of BSFL in dog foods by American consumers was preferred over mealworms and ants. As a result, the researchers stated that overall; BSFL is almost as acceptable as crickets and more acceptable than mealworms or ants (Higa et al., 2021).

In the West, there is little acceptance of eating insects due to their sensory appeal, unfamiliarity, scarcity, high cost, and negative reputation. The acceptance of food containing insects increases when the visibility of insects diminishes, and the items are appealing to the consumers (Tan et al., 2016). Studies related to BSFL demonstrated that people prefer to eat foods prepared with BSFL ingredients such as flour, fat, or protein than to eat whole insects (Delicato et al., 2020). Higa et al. (2021) reported that most of the American participants are willing to eat foods with BSFL flour or converted fat. BSFL are found a possible substitute for farmed animals that are more frequently used in pet food and are generally well liked by consumers. It can also be concluded that BSFL can also be accepted like other insects. In a paper in which different ratios of BSFL fat (0%, 25%, and 50%) were added to bakery products such as cakes, cookies, and waffles by partial substitution of butter, it was found that the addition of 25% BSFL fat did not affect the overall acceptance ad liking results. The additional amount could be increased up to 50% in waffles, even though the addition of 50% BSFL fat reduced the preference, and caused a rancid aroma and off-flavor. It was also mentioned that the addition of butter gained a similar structure and functionality to the addition of butter (Delicato et al., 2020).

One of the key elements in winning over customers is their perception of the safety of eating insects, including BSFL (Bessa et al., 2020). Increasing the consumption of BSF products represents a promising approach to addressing multiple global challenges. BSF-based products, such as edible insect protein and oils, not only provide a sustainable and eco-friendly source of nutrition, but also have the potential to significantly reduce the environmental footprint associated with traditional livestock farming. As the world grapples with issues like food security, resource scarcity, and climate change, promoting the consumption of BSF products offers a viable solution. To encourage greater adoption, it is essential to raise awareness about the nutritional benefits of BSF, develop appealing culinary options, and establish clear and supportive regulatory frameworks. As more people embrace the concept of entomophagy (insect consumption) and recognize the positive environmental impact, the consumption of BSF products is poised to become an integral part of the global food system.

2.9 Regulatory framework of BSF farming and their products

The lack of clear regulatory guidelines concerning the utilization of BSFL as animal feed restricts their commercialization. The European Union, Australia, Canada, and the USA have established certain conditions that permit the trade and production of BSFL as animal feed. Notably, in many countries where insect consumption is a traditional practice, there is a notable absence of specific regulations governing their use as feed, and efforts are underway to develop regulatory frameworks. Gaining a comprehensive understanding of the legal framework is crucial for achieving consistency in the large-scale production of BSFL as animal feed (Alagappan et al., 2022a, 2022b). As outlined by Raman et al. (2022), the legal framework for the consumption of BSFL necessitates standardization of regulations and procedures between the central regulatory authority and individual states. It also calls for the implementation of routine inspections to mitigate the potential odor issues emanating from BSFL rearing areas and the introduction of halal certification to establish a standardized list of substrates permissible for use as feed for BSFL. Nevertheless, it is imperative to consider factors like the sources of raw materials used for BSFL production, including their characteristics such as chemical composition, initial microbiological status, presence of pathogens, heavy metals, and so forth. Additionally, the methods employed for processing BSFL, such as extraction and drying, as well as the attributes of the final product, including microbiological safety and heavy metal content, should be carefully accounted for. Legal regulations should be developed within this framework.

3 Enhancing bioconversion rate of black soldier fly treatment

3.1 Pre-treatment and types of larval diet

3.1.1 Pre-treatment

The sustainable production of BSFL requires access to an adequate growing substrate. Among the different options available, organic waste is particularly advantageous due to its dependability and affordability. Furthermore, the use of organic waste as a substrate for BSFL cultivation can contribute to the management of agricultural by-products and waste pollution. By utilizing organic waste, BSFL can produce both protein and energy, while also generating organic waste residue that has a potential for a fertilizer (Fitriana et al., 2022). The potential of BSFL to decompose waste within a defined period can be assessed through the utilization of the waste reduction index (WRI, Eq. 1) (Amrul et al., 2022);

$$\mathrm{WRI} = \frac{(W - R)}{W \times t} \times 100 \tag{1}$$

W: the amount of substrate; R: the amount of residue; t: time.

Although BSFL have a high tolerance for nutrient-poor substrates, the physical and chemical quality of the substrate has a significant impact on the nutrient composition and production of BSFL (Bonelli et al., 2020; Ewald et al., 2020; Fitriana et al., 2022; Galassi et al., 2021; Meneguz et al., 2018a, 2018b). The issue of the copious quantity of fiber present in agricultural waste is of significant concern, primarily due to its lignocellulosic nature that impedes the digestion process of BSFL. To address this drawback, it is imperative to augment the feedstock quantity. However, it is essential to note that not all feedstocks exhibit the same effect on larval growth and survival, and can be ameliorated through the implementation of some pre-treatment techniques (Ee et al., 2022; Raksasat et al., 2020, 2021). Peguero et al., (2022) categorized these under three groups, i.e., physical, chemical, and biological techniques.

In the realm of physical pre-treatments, additives are unnecessary, yet the demands placed upon them vary depending on the technology employed, the type of substrate, and the desired outcome (Bhagwat et al., 2015; Peguero et al., 2022). Through the artistry of mechanical pre-treatment, substrate ps can be diminished in size using an array of choppers and mills (Oyedeji et al., 2020; Peguero et al., 2022). Meanwhile, the efficacy of thermal pre-treatment relies heavily upon temperature, pressure, and time, necessitating temperatures surpassing 100 °C and processing times spanning from 15 to 120 min, under 2–9 bar pressure. Nevertheless, these conditions may prove unsuitable for the processing of BSFL, due to the potential inactivation of advantageous microorganisms residing within the substrate. Consequently, pre-treatment at lower temperatures (ranging from 80 to 90 °C) and prolonged holding periods (60 min) may serve as a more fitting treatment regimen for the substrate prior to BSFL bioconversion, all while ensuring the pasteurization of related substrate (Atelge et al., 2020; Gold et al., 2020a and 2020b; Peguero et al., 2022). For instance, 75 °C was recorded as a threshold value for hydrolyzing waste-activated sludge efficiently during the rearing of BSFL (Liew et al., 2022a).

A commonly employed strategy for chemical pre-treatment involves the use of enzymatic hydrolysis to eliminate anti-nutritional compounds and enhance nutrient levels. Soybean meal is the preferred plant-based protein for such pre-treatment, as it is readily available and contains higher levels of anti-nutritional factors than other food waste products.

Numerous studies have demonstrated that enzyme pre-treatment leads to better growth performance and feed intake compared to untreated samples. Furthermore, solid-state enzymatic hydrolysis is a promising method for reducing the fiber content and enhancing the nutritional value of brewer's spent grain (Liang et al., 2022; Martinez–Antequera et al., 2022; Sampathkumar et al., 2023). Moreover, chemical pre-treatments involving alkalis or acids have been found to reduce the level of cellulose crystallinity and enhance the production of sugars. Among these interventions, the use of urea is considered cost-effective and safe. However, it only leads to a modest increase of 10–17% in the degradability of rice straw. Alternatively, oxidative substances like per acetic acid can be utilized for biomass treatment, but their non-selective nature may result in the degradation of cellulose and hemicellulose components (Chaturvedi & Verma, 2013; Hendriks & Zeeman, 2009; Sarkar et al., 2012; Sarnklong et al., 2010; Van Kuijk et al., 2015). In a study conducted by Isibika et al. (2019), BSFL cultivated on dessert peel enriched with nitrogen (specifically, banana peel treated with ammonia) exhibited larger sizes and a higher rate of bioconversion compared to dessert peel that was not pre-treated. The significant increase in larvae weights and bioconversion rate observed in the ammonia pre-treatments indicates the potential of the BSFL process to convert non-protein nitrogen into protein.

One of the biological methods is the fermentation processes carried out by different microorganisms, and they can be categorized into two types depending on how they are introduced. In situ fermentation refers to the simultaneous execution of the fermentation process and the valorization of organic substrates by BSFL. On the other hand, ex situ fermentation involves the early fermentation of organic substrates by microorganisms, before they are fed to the BSFL. Microbial fermentation is essential for the breakdown of complex components through hydrolysis, and the release of nutritional by-products to enhance the palatability of BSFL (Mohd–Noor et al., 2017; Raksasat et al., 2020; Wong, Aris, et al., 2020). Pre-treatment methods, such as washing, have been demonstrated to enhance nutritional compositions when used in combination with fermentation (Sampathkumar et al., 2023).

The degradation of lignin by wood decay fungi presents a distinctive avenue for enhancing lignocellulosic biomass for use as a feed in BSFL production. Nevertheless, implementing biological pre-treatment of biomass on an industrial level is challenging due to the requirement of sterilized conditions, significant consumption of cellulose derivatives by fungal species, and the prolonged duration of the process (Chaturvedi & Verma, 2013; Van Kuijk et al., 2015). Employing particular fungi, refining cultivation conditions, and introducing fungi via spawn technology can surmount drawbacks and render fungal treatment of lignocellulosic biomaterials a substitute for some chemical and/or physical approaches (Van Kuijk et al., 2015).

3.1.2 Various substrates for larval feeding

BSFL consume substantial quantities of decaying plant and animal matter, which encompass decomposing fruits, vegetables, food items, heaps of cow and poultry excrement, along with human and animal waste, exclusively during their larval phase (Fig. 2). The adult flies deposit their eggs in dry crevices near locations with damp organic waste, such as compost heaps or landfill sites, which serve as breeding grounds. The laying of eggs and the development of the larvae are markedly affected by non-living factors, including temperature, relative humidity, the source of light, and various characteristics associated with the waste (such as pH and moisture content) (Sheppard et al., 2002;

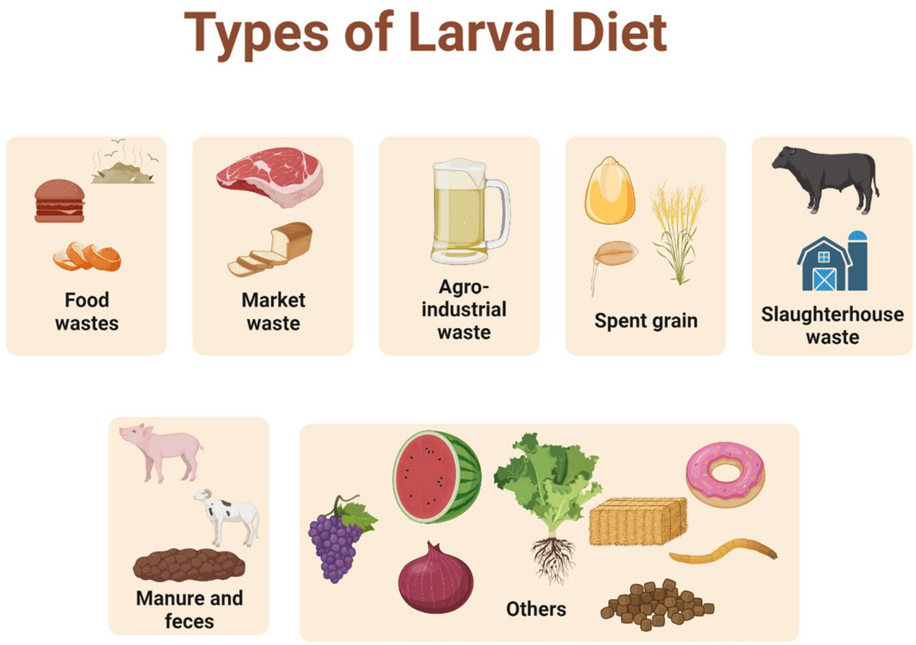

Fig. 2 Various kinds of substrates for BSFL feeding (created with Biorender.com)

Singh & Kumari et al., 2019; Üstüner et al., 2003). As a result, their distinct biological and ecological properties allow BSFL to be adapted to a wide range of organic waste substrates. The adaptability of BSFL to the organic waste subtrates may be related to versatile digestive system, detoxification mechanisms, selective feeding, microbial synergy, waste preferences, etc. Gaining an understanding of these mechanisms can assist in utilizing their adaptability for sustainable food production and effective waste utilization. Therefore, using BSF larvae's adaptability for sustainable food production and waste management requires a comprehensive strategy that takes into account environmental control, waste substrate selection, and ongoing research to maximize the larvae's performance in a variety of waste streams.

3.1.2.1 Food waste Roughly 32% of the world's food production, amounting to approximately 1.3 billion tons, is lost or wasted on an annual basis (FAO, 2017). The utilization of food waste as larval feed presents a resolution that effectively tackles waste management and food security issues, concurrently alleviating the necessity to cultivate traditional feed resources. Diverse varieties of food losses and waste possess inherent nutritional value and can be transformed into safe feed alternatives through contemporary methodologies (Rajeh et al., 2021). Several researchers have used kitchen waste (Deng et al., 2022; Li et al., 2022a, 2022b; Shumo et al., 2019), vegetable waste (Gold et al., 2020c; Julita et al., 2018; Pamintuan et al., 2019; Spranghers et al., 2017), raw food waste (Fu et al., 2022), fast food waste (Holeh et al., 2022), juice, banana, and dessert peel (Isibika et al., 2019, 2021), orange peel (Isibika et al., 2021) and leftover of some fruits and vegetables (Barbi et al., 2020), for BSFL feeding (Table 2).

3.1.2.2 Market waste The retail sector plays a crucial role in the food supply chain, generating lesser quantities of waste compared to other stages. Among the various types of waste, meat, and bread have the greatest impact on the environmental footprint of supermarkets. Consequently, addressing meat and bread waste becomes a pivotal aspect in the pursuit of reducing the environmental impact of supermarkets. An investigation was conducted into alternative waste treatment methods involving the separation of packaging from food waste at the source, and the usage of bread as animal feed. The findings reveal that these methods possess the potential to significantly decrease the carbon footprint of the supermarket (Brancoli et al., 2017). Similarly, market waste (Holeh et al., 2022) and supermarket food waste (Van Looveren et al., 2023) were investigated (Table 2), whether they had the potential as a substrate for BSFL.

3.1.2.3 Agro-industrial waste The rise of industrialization and globalization, along with an increase in population, has significantly contributed to the escalation of industrial and agricultural pursuits worldwide. Consequently, substantial amounts of agro-industrial food waste are generated annually from commercial farms and households, as well as food processing facilities (Aruna et al., 2017; Sadh et al., 2018; Yafetto et al., 2023). The utilization of agro-industrial residues as primary resources can contribute to the alleviation of production expenses, as well as the mitigation of environmental pollution. These residues are employed in the production of animal feed via the process of solid-state fermentation. Numerous microorganisms are harnessed for the synthesis of these valuable commodities (Sadh et al., 2018). For BSFL rearing, brewer's waste (Liu et al., 2018), pulp and paper industry biosludge (Norgren et al., 2020), and mill by-products (Gold et al., 2020c) have been studied (Table 2).

3.1.2.4 Spent grain The by-product that is most commonly produced in the process of brewing beer is known as brewer's spent grain. This material is primarily comprised of barley grain husks, which are left over as a solid residue after wort production. Brewer's spent grain is a valuable source of both protein and fiber. So far, the primary use for this by-product has been as feed for animals (Lynch et al., 2016). Table 3 depicts the nutritional compositions of spent grains declared in different papers (Heckmann & Gligorescu, 2019; Peguero et al., 2023; Shumo et al., 2019).

3.1.2.5 Slaughterhouse waste On a global scale, slaughterhouses produce significant quantities of animal by-products. These by-products hold great potential as a valuable source of industrial protein that could be effectively utilized in a variety of value-added applications. However, at present, they are either not fully utilized in high-value applications or primarily used in the production of pet food and animal feed. Additionally, certain by-products from animal slaughtering lead to a pressing environmental concern regarding their disposal (Adhikari et al., 2018). Mostly, fish wastes (Isibika et al., 2021; Pamintuan et al., 2019) were chosen as substrates for BSF larval feeding, compared to poultry slaughterhouse waste (Gold et al., 2020c).

3.1.2.6 Manure and feces Animal manure refers to the excretions of animals, specifically their urine and feces, along with bedding materials. It is commonly utilized as a means of enriching soils for the purpose of fostering agricultural production. Historically, animal manure has held significant value in agricultural practices and continues to serve as an indispensable fertilizer for organic farming. In fact, prior to the widespread implementation

Table 3 Nutritional composition of different substrates (%) for feeding BSFL based on reported studies from 2009 to 2023

Year	Substrate	Protein	Fat	Total carbohydrate	Ash	Reference
2009	Housefly maggot meal	47.6	25.3	NA	6.25	Aniebo et al., (2009)
2012	Fish meal	64.1*	9.8*	NA	16.6*	Kroeckel et al., (2012)
2016	Fish meal	63.3*	9.7*	NA	16.1*	Surendra et al., (2016)
2016	Soybean meal	43.9*	1.2*	NA	6.4*	
2022	Palm kernel meal (fermented)	47.34	4.31	33.34	13.18	Suprihanto and Rudianto, (2022)
2020	Chicken feed	21.0*	4.1*	NA	6.0*	Gligorescu et al., (2020)
2023	Chicken feed	19.77*	5.28*	NA	5.19*	El Deen et al., (2023)
2017	Chicken feed	175*	NA	889*	115*	Spranghers et al., (2017)
2017	Vegetable waste	86*	NA	1121*	108*	
2019	Vegetable waste	31.95	40.55	15.20	15.20	Pamintuan et al., (2019)
2020	Vegetable canteen waste	12.1	28.9	NA	Gold et al., (2020c)	
2018	Vegetable waste + horse manure	13.89	3.51	37.40	21.80	Julita et al., (2018)
2018	Vegetable waste + sheep manure	16.43	3.87	41.61	20.45	
2023	Vegetable waste + fruit waste	27.5–35.9	0.9–1.4	16.8–27.3	2.6–6.8	Humpy et al., (2023)
2017	Restaurant waste	157*	NA	700*	45*	Spranghers et al., (2017)
2022	Market waste	46.52*	NA		10.08*	Holeh et al., (2022)
2022	Hotel waste	45.29*			9.03*	
2023	Fast food waste	18.09*	27.74*	NA	3.13*	El Deen et al., (2023)
2023	Secondary sludge of slaughter waste	26.60*	27.38*	NA	3.49*	
2023	Supermarket food waste	3.5	1.0	15.3	NA	Van Looveren et al., (2023)
2023	Supermarket food waste with fish and meat	8.0	3.4	11.1		
2018	Brewer's waste	22.6*	5.8*	NA	3.7*	Liu et al., (2018)
2018	Barley + brewer's yeast	31.99*	5.39*	NA	4.74*	Chia et al., (2018a)
2018	Barley + malt + brewer's yeast	30.22*	6.96*		4.41*	
2018	Barley + sorgum + brewer's yeast	31.39*	9.48*		4.32*	
2018	Corn starch + malt + brewer's yeast	27.72*	6.04*		5.14*	
2018	Malt + barley + molasses + brewer's yeast	22.32*	3.23*		4.08*	

Table 3 (continued)

Year	Substrate	Protein	Fat	Total carbohydrate	Ash	Reference
2018	Sorgum + barley + molasses + brewer's yeast	21.69*	5.18*		4.71*	
2018	Malt + corn starch + molasses + brewer's yeast	19.10*	3.42*		4.31*	
2022	Raw food waste	36.93	26.9	7.77	NA	Fu et al., (2022)
2022	Kitchen waste	25.41	13.37	28.92	10.52	Li et al., (2022a, 2022b)
2022	Kitchen waste	22.86*	20.77*	42.16*	NA	Deng et al., (2022)
2019	Kitchen waste	20.0*	NA		7.2*	Shumo et al., (2019)
2020	Canteen waste	32.2	34.9	NA		Gold et al., (2020c)
2020	Poultry slaughterhouse waste	37.3	42.9			
2021	Fish waste	15.9	5.8	2.1	NA	Isibika et al., (2021)
2022	Fish meal	69.3*	6.9*	NA	12.2*	Fahrur et al., (2021)
2023	Grass clippings	14.0*	< 5.0*	NA		Peguero et al., (2023)
2018	Semi-digestated grass	15.0*	1.4*	NA	7.5*	Liu et al., (2018)
2017	Digestate	246*	NA	779*	299*	Spranghers et al., (2017)
2022	Digestate (hydrogen)	39.83	24.63	6.83	NA	Fu et al., (2022)
2022	Digestate (methan)	51.35	21.20	9.07	NA	
2023	Mixed pig manure	8.22*	0	NA	5.45*	El Deen et al., (2023)
2018	Pig manure	26.6*	1.2*	NA	13.7*	Liu et al., (2018)
2023	Nursery pig manure	28.92	3.37	5.69 +	NA	Hao et al., (2023)
2023	Growing pig manure	22.60	3.64	5.49 +		
2023	Finishing pig manure	19.31	3.42	6.08 +		
2018	Sheep manure	13.34	4.27	40.17	21.45	Julita et al., (2018)
2018	Horse manure	10.13	3.87	51.97	14.15	
2019	Chicken manure	15.3*	NA		20.2*	Shumo et al., (2019)
2019	Chicken manure	28.91	4.37	NA	NA	Rehman et al., (2019)
2019	Dairy manure	20.18	2.04	NA	NA	

Table 3 (continued)

Year	Substrate	Protein	Fat	Total carbohydrate	Ash	Reference
2020	Duck manure	18.90	0.67	29.53	50.9	Pamintuan et al., (2020)
2020	Cow manure	11.1	4.4	NA		Gold et al., (2020c)
2022	Cow manure (fermented)	46.64	4.47	35.45	11.14	Suprihanto and Rudianto, (2022)
2023	Cow manure	9.1*	4.4*	NA	NA	Peguero et al., (2023)
2019	Seaweed	1	0	8	4	Heckmann and Gligorescu, (2019)
2019	Milkfish offal	38.95	10.08	44.45	6.53	Pamintuan et al., (2019)
2019	Chick mash	34.75	17.25	35.85	12.15	
2019	Spent grain	12.2*	NA		6.2*	Shumo et al., (2019)
2019	Spent grain	6	3	15	1	Heckmann and Gligorescu, (2019)
2023	Spent grain	24.5*	2.9*	NA	NA	Peguero et al., (2023)
2021	Spent coffee	4.80	5.14	NA	0.47	Fischer et al., (2021)
2021	Maize distillers	29.5*	94.9**		5.40*	Galassi et al., (2021)
2021	Okara	39.2*	18.3**		4.13*	
2022	Okara	23.24	9.19	30.15	4.33	Li et al., (2022a, 2022b)
2023	Okara	19.41*	4.06*	NA	2.19*	Muin et al., (2023)
2019	Juice peel	5.38*	1.3*	12.2++	NA	Isibika et al., (2019)
2019	Dessert peel	5.50*	1.4*	13.6++		
2021	Banana peel	0.9	1.1	6.6	NA	Isibika et al., (2021)
2021	Orange peel	1.1	0.3	14.1		
2019	Sugarbeet top	4	0	6	3	Heckmann and Gligorescu, (2019)
2019	Rapeseed cake	32	9	44	7	
2020	Pulp and paper industry biosludge	1.5	1.7	13.6	NA	Norgren et al., (2020)
2020	Rice straw	34.62	8.00	39.45	17.92	Pamintuan et al., (2020)
2020	Mill by-products	14.5	3.0	NA		Gold et al., (2020c)
2020	Almond by-products	40.1–67.7	14.6–31.0	56.85–341.73+	NA	Palma et al. (2018)

Table 3 (continued)

Year	Substrate	Protein	Fat	Total carbohydrate	Ash	Reference
2020	Exotic fruit leftover	0.72	0.08	15.44	0.48	Barbi et al., (2020)
2020	Melon leftover	0.48	0.08	0.00	0.71	
2020	Pineapple leftover	0.52	0.21	11.39	0.62	
2020	Corn leftover	11.49	1.44	0.30	0.97	
2020	Peach leftover	0.87	0.82	4.30	0.52	
2020	Tomato leftover	3.02	0.37	0.00	0.82	
2020	Kiwi leftover	0.94	0.05	7.36	1.73	
2020	Legume leftover	16.98	0.70	6.33	1.05	
2020	Pomace leftover	1.97	3.67	1.08	8.23	
2019	Danish cookie	6	21	70	0	Heckmann and Gligorescu, (2019)
2021	Donut dough	10.29	8.71	NA	0.91	Fischer et al., (2021)
2021	Brewer's grains	15.8*	15.8**		4.13*	Galassi et al., (2021)
2019	Malt	22	3	62	7	Heckmann and Gligorescu, (2019)
2019	Wheat	11	2	73	1	
2022	Wheat bran	15.1	2.73	61.6	NA	Ribeiro et al., (2022)
2023	Wheat bran	15.81*	3.52*	NA	2.62*	Zhang et al., (2023a)
2022	Wheat bran + alfalafa meal + corn meal	12.46*	3.29*	30.08 +	4.98*	Arabzadeh et al., (2022)
2019	Apple pomace	1	1	17	1	Heckmann and Gligorescu, (2019)
2022	Apple	0.3	0.2	13.8	NA	Ribeiro et al., (2022)
2022	Spinach	2.9	0.6	2.6		
2022	Grape pomace	5.8	2.8	13.0		
2022	Pumpkin	1.0	0.1	10.5		
2022	Red onion	0.9	0.1	9.9		
2022	Red cabbage	1.4	0.2	7.4		
2022	Chinese cabbage	21.42*	1.42*	45.71*	NA	Deng et al., (2022)

Table 3 (continued)

Year	Substrate	Protein	Fat	Total carbohydrate	Ash	Reference
2020	Biopulp	25.4*	17.2*	NA	2.4*	Gligorescu et al., (2020)
2022	Coffee grounds + biopulps with husk	19.78–22.70*	20.74–30.54*	38.60–51.83*	6.34–8.16*	Gligorescu et al., (2022)
2022	Fruit + vegetable + bakery + brewery	19.66*	8.26*	41.33 +	4.16*	Arabzadeh et al., (2022)
2022	Sweet potato	1.81	0.33	NA	0.86	Romano et al., (2022)
2023	Tangerine	0.11*	0.05*	NA	0.05*	Scieuzo et al., (2023)
2023	Strawberry	0.06*	0.03*		0.04*	
2023	Orange	0.12*	0.02*		0.08*	
2023	Mushroom stems	6.18*	0	NA	3.44*	El Deen et al., (2023)
2023	Oat pulp	36.3*	5–12*	NA	NA	Peguero et al., (2023)
2022	Soybean curd residue	23.24	9.19	4.33	30.15	Li et al., (2022a, 2022b)
2023	Desiccated coconut residue	3.81*	22.36*	NA	0.80*	Muin et al., (2023)
2023	Bioflocs	34.52*	3.46*	NA	31.68*	Zhang et al., (2023a)

NA not available

*Dry matter, **Total amount of fat and carbohydrate on dry basis, +Total amount of starch and sugar, ++Soluble carbohydrate on dry basis of synthetic fertilizers, a substantial portion of external nutrient inputs for cultivated crops stemmed from animal manure (He, 2012, 2020; Pagliari et al., 2019). Lots of manures have been evaluated as an alternative feed for BSFL, such as pig (El Deen et al., 2023; Hao et al., 2023; Liu et al., 2018), sheep and horse (Julita et al., 2018), chicken (Rehman et al., 2019; Shumo et al., 2019), dairy (Rehman et al., 2019), duck (Pamintuan et al., 2020) and cow (Gold et al., 2020c; Peguero et al., 2023; Suprihanto & Rudianto, 2022).

3.1.2.7 The others With the exception of the above-mentioned substrate groups, various animal feeds, and meals (Aniebo et al., 2009; El Deen et al., 2023; Fahrur et al., 2021; Gligorescu et al., 2020; Kroeckel et al., 2012), fruits and vegetables (Deng et al., 2022; Galassi et al., 2021; Li et al., 2022a, 2022b; Muin et al., 2023; Ribeiro et al., 2022; Romano et al., 2022; Scieuzo et al., 2023), digestates (Fu et al., 2022; Spranghers et al., 2017;), cereals, pulses and their derivatives (Galassi et al., 2021; Heckmann & Gligorescu, 2019; Peguero et al., 2023; Ribeiro et al., 2022; Surendra et al., 2016; Zhang et al., 2023a, 2023b) and bakeries (Fischer et al., 2021; Heckmann & Gligorescu, 2019) have the potential for feeding *H. illucens* larvae (Table 3).

3.1.3 Enhance bioconversion rate through larval diet

The process of bioconversion involves the transformation of organic substances into products that possess greater biological and commercial significance. The larval phase of the *H. illucens,* is characterized by its insatiable appetite and ability to consume a diverse range of organic materials (Scieuzo et al., 2023). Despite variations in the concentration of crude protein, lipid, and carbohydrates depending on substrate (Table 2), the profiles of both fatty acid and amino acid remain relatively consistent. The growth-related parameters of insects, such as specific growth rate and bioconversion efficiency, are influenced by various factors. In terms of waste consumption, BSFL demonstrated the highest consumption rate for fruits and vegetables, compared to standard poultry feed, kitchen waste, pig liver, and manure (Barragan–Fonseca et al., 2018; Nguyen et al., 2015; Ravi et al., 2020). On the contrary, research conducted using plant-based diets has shown that regimes consisting mainly of fruits and vegetables result in a longer duration of larval development (Arabzadeh et al., 2022), therefore some modifications playing around with their nutritional values should be performed in BSFL feeding substrates. For instance, different combinations of barley, sorghum, malt, brewer's yeast, corn starch, and molasses were used in the formulation, and outstanding protein and fat content were determined in sorghum + barley + brewer's yeast mixture on a dry basis (Chia et al., 2018a, 2018b). Accordingly, the development of BSFL relies heavily on the optimization of the mixing ratio, where nutritious organic wastes can be effectively introduced as co-substrates (Liew et al., 2022b). By systematically blending sewage sludge and chicken manure in a 1:4 ratio, an impressive surge was observed in the biomass conversion rate, soaring from a mere 1% to a remarkable 8% (Cai et al., 2018). Furthermore, the weight of BSFL is solely determined by their diet during the larval stage (Mohan et al., 2022). If an individual consumes a diet that lacks sufficient nutritional value, the duration required for their development into pre-pupae may be prolonged by up to a maximum of two months (Ermolaev et al., 2019; Purkayastha & Sarkar, 2022). A diet abundant in protein or waste material greatly expedites the development of the larvae, as they rapidly accumulate the essential protein needed for their growth and save significant amounts of energy in the process (Purkayastha & Sarkar, 2022).

Considerable attention has been devoted to the ratio between lignocellulosic material and feedstock that is rich in protein (C/N) in the blending method. However, it is important to note that the true protein content, excluding non-protein nitrogen, is what determines the overall crude protein levels. In addition to C/N ratio, the selection of the protein which is mixed with agricultural leftovers is a significant factor to consider in this procedure, as well. Examples of potential protein sources for BSFL include cell protein, sewage sludge, and so on (Ee et al., 2022; Lim et al., 2019; Raksasat et al., 2021).

The BSF bioconversion procedure is carried out by directly feeding the larvae without moistening the substrate. However, investigations about the bioconversion of some kinds of diets revealed that moisture content adjustment had a substantial effect on larval growth. Because moisture content has a significant effect on the bioconversion of BSF, it is critical to evaluate the impact of moisture content of food waste utilized as growing media to ensure influential food waste treatment (Khairuddin et al., 2022).

In order to guarantee the sustainability of BSFL production, it is vital to comprehend and enhance bioconversion efficiency which refers to the percentage of nutrients supplied in the substrate that are integrated into larval biomass. The greater the conversion efficiencies, the more optimal the sustainability outcomes of the system (Bosch et al., 2019; Parodi et al., 2020). Also "bioconversion rate" term gains importance in this way, and can be calculated as follows (Rehman et al., 2019);

$$\text{Bioconversion rate} = \frac{\textit{Total biomass of larvae}}{\textit{Total amount of feed}} \times 100 \tag{2}$$

Table 4 demonstrates survival and bioconversion rates as percentages, and durations of treatments of BSFL, with changing substrate types and/or amounts. It is obvious that the survival rate could be enhanced by combining different substrates, and the lowest scores are usually belonged to sludge (Lalander et al., 2019), fish, mussels, and bread (Ewald et al., 2020) substrates. The superior survival rates are calculated in aquaculture and abattoir waste (above 100%) (Lalander et al., 2019), spent coffee (Isibika et al., 2021), and pig manure (Wu et al., 2023), as well as wheat bran (Zhang et al., 2022). Regarding bioconversion percent, sweet potato and dough (Romano et al., 2022), soybean dregs + corn straw biochar (Qin et al., 2022), human feces (Lopes et al., 2022), poultry feed (Gold et al., 2020b) and bioflocs and combinations (Zhang et al., 2023a, 2023b) have successful results.

3.2 Adding beneficial microbial and additive compound

The effectiveness of microbial supplements in altering the nutritional substrate for BSFL is currently unsupported by practical evidence (Wong et al., 2020a, 2020b). However, some limited research is available in the literature. For example, in their study, Yu et al., (2011) found that the addition of *Bacillus subtilis* (four strains) to the feeding medium of BSFL resulted in higher pre-pupal weight and improved survival rates during the transition from pre-pupae to pupae, compared to the control group. Similarly, *B. subtilis* inoculated group exhibited a reduction rate of 40.5% in chicken manure, whereas the control group showed a reduction rate of 35.8%. The weight of BSFL and conversion rate increased by 15.9% and 12.7%, respectively, and the reduction rate of chicken manure increased by 13.4% in comparison with the control (Xiao et al., 2018). Moreover, Wong et al., (2020a, 2020b) dedicated their research to harnessing the incredible potential of exo-microbes, specifically in the form of a bacterial consortium powder. Through a meticulous fermentation process, they sought to transform coconut

Table 4 Survival and bioconversion rates as well as treatment durations of substrates for feeding BSFL

Year	Substrate	Survival rate (%)	Bioconversion rate (%)	Treatment duration (day)	Reference
2017	Dairy manure + chicken manure	91.86–96.41	5.88–7.90	18.57–21.36	Rehman, Cai, et al., (2017)
2017	Dairy manure	89.45	4.19	22.03	
2017	Chicken manure	98.35	9.88	18.34	
2022	Soybean curd residue: kitchen waste (30:70)	81.50–99.50	13.04–18.54	12	Li et al., (2022a, 2022b)
2022	Soybean dregs + corn straw biochar	82.0–95.3	24.36–25.59	10	Qin et al., (2022)
2017	Soybean curd residue + dairy manure	91–99	6.3–15.2	19–23	Rehman et al., (2017a, 2017b)
2019	Soybean curd residue	95.4	5	17.7	Somroo et al., (2019)
2019	Soybean curd residue (*Lactobacillus burnerii*)	98	6.9	16.1	
2019	Artificial feed	94	3.9	18.3	
2019	Dog food	89	13.4	15	Lalander et al., (2019)
2019	Poultry manure	92.7	7.1	14	
2019	Poultry feed	93	12.8	14	
2019	Digested sludge	39	0.2	39–42	
2019	Undigested sludge	76.2	2.2	30	
2019	Primary sludge	81	2.3	16–21	
2019	Human feces	91.8	11.3	12	
2019	Abattoir fruit and vegetable	96.3	14.2	12	
2019	Abattoir waste	101.5	15.2	12	
2019	Food waste	87.2	13.9	14	
2020	Aquaculture waste	101	23.9	12	Lopes et al., (2020)
2020	Aquaculture waste + bread waste	18.6–96.8	5.8–24.9	12–18	
2020	Mill by-products	96.2	14.9	12–14	Gold et al., (2020b)
2020	Human feces	96.2–99.1	18.8–22.7		
2020	Cow manure	89.8	3.8		
2020	Vegetable canteen waste	97.5	22.7		
2020	Canteen waste	92.3	15.3		
2020	Poultry feed	97.9	21.0		

Table 4 (continued)

Year	Substrate	Survival rate (%)	Bioconversion rate (%)	Treatment duration (day)	Reference
2020	Poultry slaughterhouse waste	90.7	13.4		
2020	Bread	69.8	13.4	14	Ewald et al., (2020)
2020	Fish	18.4	2.4		
2020	Food waste	89.1	18.9		
2020	Mussels (fresh/ensiled/rotten)	11.0–89.3	< 0.1–0.8		
2020	Bread and mussels	54.3–86.2	3.6–11.5		
2021	Fish meal + orange peel + banana peel	35.6–100	2.3–25.3	14–21	Isibika et al., (2021)
2022	Spent coffee	98.6	38.7	14	Romano et al., (2022)
2022	Sweet potato	87.0	23.0		
2022	Dough	83.3	55.8		
2022	Wheat bran	94.27–98.00	6.71–9.17	17.5–19	Zhang et al., (2022)
2022	Wheat bran	87.00	15.68	20	Bohm et al., (2022)
2022	Household food waste	92.00	9.98		
2022	Dewatered sludge	83.00	7.08		
2022	Dewatered sludge + wheat bran	95.00	13.84		
2022	Dewatered sludge + household food waste	82.00	16.10		
2022	Digester sludge + wheat bran	92.00	14.60		
2023	Sewage sludge	68	6.01	24	Mishra and Suthar, (2023)
2023	Sewage sludge: fruit waste (70:30)	79	14.25	24.67	
2023	Sewage sludge: fruit waste (50:50)	88.67	13.67	26.67	
2023	Sewage sludge: fruit waste (30:70)	92.67	9.19	22	
2023	Fruit waste	96.33	14.18	25.67	
2023	Cow manure	91.1–96.1	1.6–3.8	12–16	Peguero et al., (2023)
2023	Grass clippings	87.3–98.9	1.1–4.3		
2023	Oat pulp	98.2–99.5	3.0–18.8		

Table 4 (continued)

Year	Substrate	Survival rate (%)	Bioconversion rate (%)	Treatment duration (day)	Reference
2023	Spent grain	95.7–98.9	3.1–11.5		
2023	Fresh pig manure	95.67	4.94	10	Wu et al., (2023)
2023	Pig manure (aerobic)	94.00–94.33	3.81–4.34		
2023	Pig manure (anaerobic)	95.67–96.00	5.20–6.49		
2023	Pig manure (high temperature anaerobic)	97.33–98.67	7.01–7.32		
2023	Chicken manure	91.33	5.21	10	Zhang et al., (2023b)
2023	Chicken manure + biochar	93.33–96.67	6.87–8.31		
2023	Bioflocs	91.08	18.29	16	Zhang et al., (2023a)
2023	Bioflocs: wheat bran (60:40)	95.50	23.91		
2023	Oil palm biowaste	44.00–96.67	9.2–13.7	15	Bajra et al., (2023)

endosperm waste into a more delectable and nutritious feed for BSFL, increasing the accumulation of vital lipids and proteins. Remarkably, the most favorable fermentation conditions were achieved by introducing a mere 0.5% of the bacterial consortium powder (w/w) into the waste, allowing it to ferment for a period of 14–21 days. It is noteworthy that BSFL biomass and growth rate reached their pinnacle when nourished with this optimum fermented coconut endosperm waste. Somroo et al. (2019) pre-treated soybean curd residue with *Lactobacillus buchneri* and stated that *L. buchneri* exhibited a substantial enhancement in bioconversion rate, crude protein and fat levels. Nevertheless, the feed conversion ratio of BSFL fed with soybean curd residue and *L. buchneri* was found to be lower than the BSFL fed with only substrate including soybean and commercially produced feed. Besides aformentioned papers, a mixture of dairy and chicken manure was fortified with *Paenibacillus plymyxa* and *B. subtilis* strains (Rehman et al., 2019), sterilized artificial diet was enriched with the aid of *Klebsiella* sp., *Proteus* sp., *Providencia* sp., *Ochrobactrum* sp., *Citrobacter* sp. and *Dysgonomonas* sp. (Li et al., 2022a, 2022b), and chicken manure was supplemented by Kocuria marina, *B. subtilis, Micrococcus luteus, Lysinibacillus boronitolerans* and *Proteus mirabilis* (Mazza et al., 2020).

Rather than microbial addition into the BSFL feed, in order to see the effects of different bacteria on BSFL rearing, two food wastes (household and canteen) were studied for enlighting the BSFL supportive microorganisms (Gold et al., 2020d), which would be helpful for forthcoming research focused on supplementation with beneficial microbial communities. During the 12-day rearing period, the presence of larvae in food wastes led to a decrease in bacterial diversity and significant changes in the physicochemical properties and composition of the residue. Additionally, certain bacteria commonly found in the larval intestinal microbiota, such as *Providencia*, *Morganella* and *Proteus*, increased in abundance, indicating their likely transfer into the residue through larval excretions.

While considering additional nutritive compounds, the inclusion of a particular carbohydrate, such as wheat starch, in the substrate utilized for the cultivation of BSFL was observed to stimulate the lipid composition of BSFL. Diets abundant in starch have demonstrated the ability to augment the synthesis of specific saturated fatty acids (Hoc et al., 2020; Nugroho et al., 2023). Accordingly, the BSFL fed a combination of palm kernel meal and fish feed pellets with 10% fructose exhibited the highest relative concentration of fatty acids. The inclusion of fructose, whether in palm kernel meal, fish feed pellets, or their combination, had a significant impact on fatty acid composition and accumulation of certain minerals, such as phosphorus, sodium, and iron in BSFL (Nugroho et al., 2023). Also, squid liver oil was added to chicken manure to increase the amount of polyunsaturated fatty acids which were lacking in BSFL, and the researchers concluded that the utilization of BSFL enriched with polyunsaturated fatty acids, docosahexaenoic acid, and eicosapentaenoic acid can be regarded as significant nutritional constituents of animal feed, while also preventing the accumulation of excessive heavy metals by feeding sustainable lipid sources in a suitable quantity (Tirtawijaya & Choi, 2022). Interestingly, the utilization of naturally occurring additives, such as propolis which is produced by honeybees, has demonstrated a promising ability to improve the performance of animals that are raised for agricultural purposes. A recent research endeavor investigated the impact of honeybee propolis extracted using ethanol on the growth performance of BSFL that consumed wheat bran. After the initial five-day period, the average weight of larvae that were raised on propolis-treated substrate exhibited a noteworthy increase in comparison with the weight of larvae reared on propolis-untreated substrate (Bakaaki et al., 2023).

3.3 Optimization of the production system

3.3.1 Abiotic factors

The practice of combining waste substrates is not always considered advantageous for the production of larval biomass due to the significant impact of pH on microbial activities. The composition of intestinal bacterial communities in insects is heavily influenced by their diet. In the context of vermicomposting production, pH is an essential factor affecting its efficiency. While the initial pH values are carefully regulated in waste management studies, pH values in digestion technology vary according to the substrate. Hence, it is critical to ascertain the ideal initial pH value for BSF digestion to enhance life history traits and biomass yield (Kim et al., 2017; Ma et al., 2018; Wang et al., 2017; Zhai et al., 2015; Zhang et al., 2012). An optimum pH range of 6 to 10 is conducive to the optimal growth and increased weight of larvae due to its ability to enhance protease activity and augment protein availability. The bioconversion process of the black soldier fly larvae leads to an elevation in substrate pH, resulting in an alkaline by-product that can be utilized for fertilization purposes. In addition, a pH range of 7 to 8 fosters plant growth and sustains bacterial populations (Amrul et al., 2022; Choi & Hassanzadeh, 2019; Surendra et al., 2020).

The average duration of the entire life cycle of *H. illucens* is approximately 40–45 days. After a period of approximately 4 days, the eggs hatch, and the larvae of the BSF emerge. If the optimal temperature (averagely 33 °C) and adequate food supply are present, this stage of development can last for approximately 14 days. Unless the temperature is optimal, the larval stage can be prolonged for up to 4 months (De Smet et al., 2018; Logan et al., 2021). On the other hand, the presence of excessive water and fats in the substrates can impede the growth of larvae, hinder their feeding, and elevate the mortality rate. Fibers that possess the capacity to hold water can avert liquid separation and furnish an improved substrate matrix for the growth of BSFL because fibers with low bulk density facilitate a greater pore volume, superior aeration, and aid in gas exchange, feeding and movement (Broeckx et al., 2021; Lopes et al., 2020; Yakti et al., 2023). In the past, composting/substrate materials were suggested to have a minimum moisture content of 50%. Nonetheless, the absence of ideal moisture contents for different materials due to their distinct features poses a challenge in applying these values to extensive composting systems, particularly those that are non-mechanized in the agricultural sector. To overcome this obstacle, innovative technologies are required to supplant conventional techniques (Chen et al., 2019; Cronje et al., 2004). Also, a relative humidity of about 60–70% and light intensity of 135–200 μmol per square meter are advised for optimal rearing. The mating and oviposition of BSFs are intricately linked to the intensity and duration of illumination, which ultimately affect their reproductive behaviors.

Adequate light is crucial for stimulating the mating process of BSF, making it susceptible to alterations during overcast days. Consequently, the absence of sufficient light during the winter season poses a hindrance to the mating activity of BSF, necessitating the utilization of artificial lighting solutions (Rehman et al., 2023; Sheppard et al., 2002; Zhang et al., 2010). The success of industries focused on cultivating BSF is heavily reliant on the fluctuations of seasons and weather conditions, predominantly those in Southeast Asia. Given the region's characteristic high temperatures and humidity, there is a tremendous opportunity for the growth and development of BSF-related industries, if they are strategically implemented in these areas (Barragan–Fonseca et al., 2017; Kim et al., 2021; Shumo et al., 2019).

3.3.2 Larval density

The density of larvae plays a pivotal role in the appropriate development and utilization of substrate in BSFL. It is advised to maintain a density of 1.2 larvae per square centimeter, as a density exceeding 5 larvae per square centimeter can have an adverse effect. This can lead to an increase in temperature, and the production of acidic leachate, which can create unfavorable conditions. However, it is noteworthy that doubling the larval density below this threshold does not affect the survival rate of BSFL, indicating the adaptability of their growth rate (Barragan–Fonseca et al., 2018; Paz et al., 2015; Purkayastha & Sarkar, 2022). Furthermore, in the cultivation of larvae, it is essential to regulate the larval density based on the substrate conditions. Recent studies have indicated that the optimal ratio of larvae to substrate for successful rearing of BSFL is 2:1 (Kim et al., 2021; Pastor et al., 2015). Moreover, high larval density leads to "intraspecies competition" between BSFs. Jones (2020) declared that the adult size of individuals was greater when the larval density was at its lowest, with 500 larvae per 4 L, as opposed to when it was at its highest, with 2000 larvae per 4 L.

3.3.3 Feeding system

The efficiency of larvae production is intricately tied to the feeding strategies employed, such as using batch or continuous systems. Unfavorable conditions have the potential to negatively impact the yield of BSFL in industrial rearing (Diener et al., 2011; Ribeiro et al., 2022). Batch feeding can result in substrate rotation and a decrease in nutrient availability, while continuous systems introduce new substrate every two or three days, potentially leading to periods of insufficient nutrients for larvae development (Dzepe et al., 2021; Mutafela, 2015; Nana et al., 2018; Ribeiro et al., 2022). An escalation in the frequency of feeding batches results in a corresponding rise in labor input (Meneguz et al., 2018a, 2018b; Zhang et al., 2021), but superior efficiency of substrate conversion could be observed by five-time batch feeding (Zhang et al., 2021). Hence, it is of utmost importance to carefully consider and incorporate both strategies in order to guarantee the utmost productivity in larvae production (Ribeiro et al., 2022).

As a consequence, optimizing the bioconversion rate of BSFL involves various strategies that consider different organic waste substrates and environmental conditions. To maximize their potential as a sustainable protein source, fertilizer, and biofuel, choosing appropriate organic waste, waste preprocessing, determining the physicochemical properties of waste substrates, controlling the environmental conditions of BSFL farming area, managing the wastes (preventing the odor, pathogens, etc.), harvest timing, controlling the biomass density, microbial management, utilization of the residual wastes, measuring the biosecurity, research and development can be considered as effective strategies.

4 Enhancing end products of black soldier fly treatment

The BSF is the insect that is most frequently used in the larval stage, due to its most nutrient-rich composition, absence of unfavorable substances like chitin, ease and low cost of raising in a variety of substrates, high bioconversion rate, the most advantageous mechanical properties, and simplicity of processing (Iñaki et al., 2022). The initial stage of BSFL processing involves the harvest, which yields a microbiologically and physicochemically safe and stable product. Subsequent processing steps, such as killing, protein, lipid, or chitin extraction, decontamination, drying, grinding, and more, can be employed based on the specific intended application of the BSFL products. Processing greatly affects the final product's quality. To ensure enhanced product quality and microbial safety, it is essential to optimize processing methods such as post-harvest conditioning (including feed withdrawal and washing), pre-treatments (such as boiling in hot water or puncturing), killing (like blanching, freezing, or applying liquid nitrogen), decontamination (utilizing high hydrostatic pressure or vacuum conditioning), drying, extraction, and other relevant techniques. During processing, BSFL lose its brightness and get darker due to the enzymatic reactions, Maillard reaction, iron and polyphenols complex formation, or oxidations that reduce the consumer acceptability and market value. Besides nutritional quality and microbial safety, optimization is needed in order to protect the color. In addition, a high amount of oxidable unsaturated fatty acid has to be considered during the processing (Larouche, 2019). When choosing a method of killing, attention should be paid to the suffering of the insects (van Huis, 2013).

The processing of larvae can lead to significant stress, resulting in a decline in their overall quality. In industrial settings, post-harvest insect conditioning often involves a period of feed withdrawal and washing as a preliminary step, before killing. The feed withdrawal method is employed to minimize the microbial load associated with the BSFL's feeding substrate and frass by allowing the larvae to be starved until their gastrointestinal system is empty. By ensuring that the BSFL have completely consumed their food, and emptying their gastrointestinal tracts prior to killing, a cost-effective reduction in microbial load can be achieved. The Food and Agriculture Organization (FAO) recommends the practice of starving insects for varying durations, ranging from a few hours to several days, depending on the species, as the exact gastrointestinal evacuation times for different species remain unknown. (Charlton et al., 2015; van Huis et al., 2013; Wynants et al., 2017). The difficulty in post-harvest conditioning is to prevent the insect from metabolizing lipids and proteins, which affects the nutritional value of the insects. Furthermore, starvation can mobilize triglycerides and glycogen that are stored in the fat body. Glycogen is mobilized initially in response to hunger, and then lipids and/or proteins may follow. Since different species have different ways of dealing with famine, the feed withdrawal process might greatly diminish the fat and protein content of the insects (Arrese & Soulages, 2010; McCue et al., 2015). Based on research findings, the average duration for feed withdrawal in BSFL typically ranges from 12 to 24 h. (Charlton et al., 2015; McCue et al., 2015). Gastrointestinal evacuation, pupariation, and feed withdrawal time (99% empty gut) of 12 days old BSFL ranged between 48 to 96 h for 184 mg larvae, 60 to 108 h, and 84 h, respectively. The feed withdrawal process affected the nutritional value of the BSFL (protein and lipid content declining with time (0–96 h)), however, this effect became significant only after 96 h (Larouche, 2019).

Blanching has emerged as a highly suitable method for killing or pre-treating BSFL, as it effectively minimizes lipid oxidation, reduces microbial contamination, and initiates the dehydration process (Larouche, 2019). Furthermore, the research on utilizing organic resources for the production of BSFL has been rapidly expanding in recent years, as the choice to use organic resources plays a pivotal role in the economic viability, environmental impact, and safety of the resulting products. The impact of different resources on factors, such as larval development time, biomass yield and quality, emissions, and residual matter (such as frass and exuvia) can exhibit significant variations.

More information is becoming available regarding the efficiency of BSFL in converting nitrogen from resources into nitrogenous biomass (Bosch et al., 2019).

Whole BSF meal, extracted protein meal, extracted oils, and numerous by-products are among these high-value marketable materials. These ingredients do share traits with conventional, occasionally less sustainable ingredients used in goods sold on different marketplaces. Currently, BSF products are used in fertilizer, biodiesel, pet food, fish feed, and cattle feed. The market shares of all current BSF-containing goods in those markets are small. Research indicates benefits for the future product market combinations of consumer food, livestock protein, pharmacies, and cosmetics (Bakker, 2020). An overview of various technologies to process BSFL is given in Table 5, as well as schematic illustration in Fig. 3.

4.1 Dried larvae

Processing such as drying is necessary for BSFL in order to facilitate its usage as feed ingredients and prevent spoilage and degradation during storage (Bogusz et al., 2022; Saucier et al., 2022). Besides, the long shelf life, the powder form of the BSFL has advantages such as dosing, mixing, and handling (Saucier et al., 2022). By adopting these approaches, the incorporation of BSFL powder into feed formulations can be accomplished effortlessly. When it comes to drying edible insects, convective hot air drying and freeze-drying are regarded as the preferred methods (Melgar–Lalanne et al., 2019). Convective hot air drying is widely employed for its simplicity, cost-effectiveness, ease of use, and continuous operation, making it a commonly utilized technique in drying edible insects. On the other hand, the final product may lose its quality such as color and nutritional value due to denaturation, oxidation, vitamin deterioration, etc. Freeze-drying is most frequently utilized, although it is expensive and requires batch processing when the quality of the dried product is prioritized (Ratti, 2001). The drying process results in lower water activity and moisture content, and a reduction in enzymatic reactions and microbial activity. The implementation of various pre-treatment methods such as blanching, scalding, and puncturing is a common practice to effectively reduce the initial microbial load and drying time, inactivate enzymes, facilitate water evaporation, lower water activity in the final product, and preserve the nutritional value. However, it is important to note that these methods are not sufficiently severe to eliminate bacterial spores (Larouche et al., 2019; Melgar–Lalanne et al., 2019; Zhen et al., 2020). Among the pre-treatment options, boiling water treatment is preferred over puncturing, as it effectively reduces microbial load while also facilitating the drying process (Saucier et al., 2022).

The drying times of BSFL were reported as 12 h and 72 h in the hot air (60 °C temperature, 1.5 m/s air flow rate, and 30% relative humidity) and freeze (40 °C shelve temperature and 0.03 Torr vacuum pressure) dryers, respectively. The pre-treatments (puncturing (50 μm holes), blanching (40 s), or scalding (2–8 min in boiling water) resulted in a higher pH and lower dry matter and ash contents, TBARS, color values, and initial microbial load (total aerobic mesophilic counts, lactic acid bacteria, coliforms, etc.) in the raw BSFL. In addition, the pre-treatments resulted in a decrease in drying time (16.7–66.7% and 33.3–80.6%), water activity and protein and lipid contents of hot air and freeze-dried samples. Freeze-dried BSFL has the advantage of oxidation reactions and brightness value, whereas hot air drying has the advantages of drying time, water activity, and microbial inactivation (Saucier et al., 2022). Huang et al., (2018) recently compared the microwave (15 min at 500 W) and oven (60 °C temperature) drying techniques to obtain BSFL flour. According to the researcher's findings, although the protein content and quality werew

Table 5 Overview of various technologies to process BSFL

Processing technology	Specifications	Outcome/effect	Advantages	Disadvantages	Reference
Feed withdrawal	Applied before killing Emptying the gastrointestinal tract (few hours to days)	Reduce the microbial load	Cheap technique for reducing microbial load	Weight loss Nutritional loss (Protein and lipid)	Arrese and Soulages, (2010) van Huis et al., (2013) Charlton et al., (2015)
Puncturing (holes)	Generally applied as s pre-treatment before drying	Improve drying efficiency	Lower drying time Ease of the water evaporation	Increase microbial load Nutritional loss Increase the oxygen accessibility	Saucier et al., (2022)
Blanching or scalding (melting the wax)	Generally applied as a pre-treatment before drying Boiling in the hot water	Decrease the microbial load Enzyme inactivation	Lower initial microbial load Lower drying time Ease of the water evaporation Reduce the water activity of the end product Protect the nutritional value Reduce lipid oxidation	Not eneogh to kill bacterial spores Slight increase in the moisture content Leaching of soluble nutrients (at the long times) Undesired structural changes	Melgar–Lalanne et al., (2019) Saucier et al., (2022)
Drying	Hot air-drying Freeze-drying Microwave-drying Sun-drying Pre-treatment before Extraction Pre-treatment before bio-diesel production	Prevent spoilage Prevent degradation	Long shelf life Easy mixing, handling, dosing Digestibility	Quality losses such as color and nutritional value (depending on the drying process)	Kamau et al., (2018) Huang et al., (2018) Bogusz et al., (2022) Saucier et al., (2022)
Freezing	Slowing the activity until death	Prevent microbial growth Prevent enzyme activity Inhibit the biochemical reactions	High nutritional quality	Expensive (time, energy, equipment)	Larouche, (2019)

Table 5 (continued)

Processing technology		Specifications	Outcome/effect	Advantages	Disadvantages	Reference
Extraction	Protein extraction	Aqueous extraction	Pure ingredient	Increase the consumer acceptability	Need for further extraction and purification Need optimization Change the flavor, the color and protein functionality	Bußler et al., (2016)
		Organic solvent extraction	Pure ingredient	Highly effective	Need optimization May be cause reactions in the protein backbone (denaturation, hydrolysis, racemization, and the creation of lysinoalanine and other cross-linked molecules)	Caligiani et al., (2018)
		Osborne fractionation protocol	Pure ingredient	Protein fraction includes negligible amounts of free –NH2 groups Highly nutritious and functional ingredient	Need optimization High cost	Caligiani et al., (2018)
		Enzyme extraction	Pure ingredient	Increase the consumer acceptability	Each enzyme needs specific conditions Need optimization Yield is lower than solvent extraction	Caligiani et al., (2018)
	Chitin extraction	Mechanical pressing Aqueous extraction Organic solvents extraction Pre-treatment before protein extraction	Pure ingredient	Increase the consumer acceptability Supplying energy and essential fatty acid	Change the flavor, the color Need optimization	Bußler et al., (2016) Tzompa–Sosa et al., (2014)
	Chitosan extraction	Chemical methods (defatting, demineralization, deproteinization, and deacetylation) Enzymatic hydrolysis Using eutectic solvents	By-product of the BSFL	High economic value Using different industries including food, medicine, and cosmetics,	Need optimization Need purifying steps Need for further studies for consumption in diferent industries	Bessa et al., (2020) Caligiani et al., (2018)

Table 5 (continued)

Processing technology	Specifications	Outcome/effect	Advantages	Disadvantages	Reference
Biodiesel Production	Two step process (acid-catalyzed esterification followed by alkali-catalyzed transesterification)	Obtaining renewable Environmentally friendly liquid fuel Alternative option to reduce petroleum consumption Minimize releasing particulates, carbon onoxide, and hydrocarbons Cheap resource Reduce the organic waste amount Having high fat content, rapid reproduction rate, and short life cycle	Reducing fat High biodiesel yield	Defects associated with the use of acid–base catalysts Eluting the catalyst is the critical step Enormous amount of wastewater High production cost, Difficulty in recovery of glycerol Crrosion induced damages to the equipment Need another treatment method need for catalyst and waste water (neutralization) High energy consumption Need optimization	Mohan et al., (2023) Nguyen et al., (2018a)
	Enzyme (biocatalyst)-catalyzed transesterification		High selectivity, Easy recovery wastewater Generation can be controlled Reusability of catalyst, Thermal stability Mildtreatment conditions	Slow reaction rate High cost, Deactivation of enzymes High contamination risk High energy consumption Need optimization	Mohan et al., (2023) Su et al., (2019) Christopher et al., (2014)
	Direct transesterification		Simultaneous lipid extraction and transesterification processes Low energy consumption Short threatment time	Includes high amount of methanol Needs a concentrated acidic catalyst Environmental issues Need optimization	Mohan et al., (2023) Nguyen et al., (2020) Nguyen et al., (2018a)
	Non-catalytic transesterification		Do not need petrochemicals Do not need lipid extraction Eco-friendly Economically viable	–	Mohan et al., (2023)

Table 5 (continued)

Processing technology	Specifications	Outcome/effect	Advantages	Disadvantages	Reference
Grinding	Mechanical application Pre-treatment before drying Obtaining the powder form	Homogenizing the size	Easy mixing, handling, dosing Fast Effective Low equipment cost Increase the surface area Reduce the drying time Preserve the nutritional quality	Increase the browning Promate the lipid oxidation	Larouche, (2019)

Fig. 3 Applications and technologies in the processing of BSFL (created with Biorender.com)

similar, the digestibility of the protein was significantly higher (exceeding 75%), when the larvae were subjected to oven drying as opposed to microwave drying.

In conclusion, the drying times, nutritional value, and quality of the BSFL depend on drying technique, drying conditions, and pre-treatments. Blanching in hot water has proven to be effective in reducing the microbial load, shortening the drying time and minimizing oxidation in the resulting dried BSFL product.

4.2 Protein meal

The concealment of insects in food significantly influences consumers' willingness to consume them. Hence, it is vital to process insects into meals and utilize their valuable nutrients, such as protein and other fractions, for food and animal feed purposes (Balzan et al., 2016). BSFL have gained popularity worldwide as an alternative protein source for animal feeds. The meal derived from BSFL is particularly valuable due to its ability to recycle lost nutrients by incorporating residual amino acids and fatty acids from manure and organic wastes into their biomass (Marco et al., 2015). In addition, the BSF is a fascinating food and animal feed ingredient due to its excellent protein digestibility (Larouche, 2019). It is possible to process and isolate the protein fraction from the oil of BSFL. The protein content of BSFL meals can reach above 60% when they are defatted (Spranghers et al., 2017). The BSFL meal exhibits a crude protein content that is comparable to or slightly higher than various plant-based proteins such as linseed meal, sunflower meal, cottonseed meal, lupins, and faba beans (St–Hilaire et al., 2007; De Marco et al., 2015). Furthermore, Caligiani et al., (2018) discovered that the amino acid composition of BSFL is on par with high-quality animal and vegetable proteins like egg white and soybean. Notably, BSFL proteins contain higher levels of tyrosine, phenylalanine, and histidine, similar amounts of lysine, threonine, and valine, and slightly lower levels of leucine, isoleucine, tryptophan, and sulfur-containing amino acids, when compared to animal and vegetable proteins.

The protein is generally extracted from BSFL using alkali extraction (solvent: NaOH), after defatting. Although alkali extraction is very effective, it has led to reactions in the protein backbone, including denaturation, hydrolysis, racemization, and the creation of lysinoalanine and other cross-linked molecules which resulted in lower functionality and nutritional value (Caligiani et al., 2018). In addition, stepwise protein extraction (Osborn: steps: aqueous extraction, salt extraction, alcohol extraction, and alkali extraction) and enzymatic hydrolysis (enzymes: papain, protease, pepsin, pancreatin, etc.) methods can be used for protein extraction from BSFL. Caligiani et al. (2018) reported that the Osborne fractionation protocol is the best extraction method for the BSF proteins in order to obtain highly nutritious and functional ingredients for feed, food, cosmetics, pharma, etc. industries. However, this protocol includes four different steps and for this reason, it is highly expensive. For enzymatic hydrolysis specific conditions for each enzyme to be considered, and the yield of this method is lower than solvent extraction (Caligiani et al., 2018).

BSFL can be accepted as a potential ingredient for chicken feed (Kawasaki et al., 2019). No significant effects were observed on the growth performance and meat quality of broiler chickens when their diets were supplemented with BSFL meal at concentrations of up to 100 g/kg. Additionally, Dabbou et al., (2018) demonstrated that a beginning broiler diet with a low level (100 g/kg) of BSFL meal may enhance growth performance. As they have shown a common finding that raising the level of BSFL meal can result in a drop in body weight, it appears that low-level inclusion of BSFL meal may be a more suitable technique (Dabbou et al., 2018; Schiavone et al., 2019). Also, the studies reported that the addition of BSFL larvae to the laying chicken feed can increase eggshell thickness, egg yolk, and albumin (Barbosa–Filho et al., 2018; Kawasaki et al., 2019).

Processing and protein extraction from insects make it easier to use certain insect-derived ingredients in food formulas. In order to produce high-quality and economical proteins from conventional protein sources for industrial biofractionation, pre-existing processing chains must be modified to match the unique needs of edible insects as raw material (Bußler et al., 2016). When unrecognizable insect protein (extract) is used in food instead of whole insects, people may be more likely to eat insect-based food. The protein from insects for use in food products is especially important for nations like Europe and North America that do not regularly consume insects (Yi et al., 2013).

4.3 Oil

The majority of the BSLF-related studies mainly focused on protein extraction; however, BSFL includes other nutritional compounds, such as lipids and chitin. The amount of fat varies greatly depending on the larval diet and can reach 49% (Barry, 2004). In order to optimize the value gained through the biorefinery approach, it is crucial to implement established protocols that can effectively recover all three primary fractions of the BSFL in consecutive stages within the same production chain. Lipid separation is very simple, while protein separation from chitin is more difficult (Gortari & Hours, 2013).

For the lipid extraction of the BSFL, harvesting, washing, inactivating, drying, extraction or pressing steps are performed. When the studies are examined, it is seen that BSFL oil is obtained by mechanical extraction (cold press) in cases, where it will be added to animal or fish feeds (Dumas et al., 2018; Li et al., 2016; Surendra et al., 2016; Xu et al., 2021).

If biodiesel is to be produced, lipid extraction from BSFL is generally accomplished by solvent extraction method (Soxhlet extraction generally using n-hexane or petroleum ether) (Ishak & Kamari, 2019; Kamari et al., 2020; Liew et al., 2023; Wang et al., 2017b). Due to the high efficiency of Soxhlet extraction method, this technique required a high amount of solvent, long extraction time, and heat applications (Li et al., 2011a). It may be the reason for the application of a mechanical press for direct consumption of BSFL oil in animal or fish feed.

Several organic dietary supplements and environmental factors can be used to properly optimize the fat content of BSFL throughout its existence. During the BSF's larval stages, enriched fat can be acquired (Mohan et al., 2023). BSFL includes higher saturated fats compared to most insects (Wang & Shelomi, 2017), and BSFL lipids are more palatable compared to vegetable oil (Iñaki et al., 2022). The high amount of lauric (46.7 ± 0.6%), oleic (15.1 ± 0.9%), myristic (8.3 ± 0.1%), palmitic (8.4 ± 0.2%), and palmitoleic (7.6 ± 0.4%) acids were determined in BSFL (Caligiani et al., 2018). For this reason, BSFL fat which is in a solid form at room temperature includes around 70% of saturated fatty acids. Moreover, lauric acid provides favorable nutritional qualities to this BSFL fat, since it is more digestible than long-chain fatty acids; it prevents the growth of various gram-positive bacteria, fungi, and viruses.

BSLF fats were used in the diet of broiler chicken as a dietary fat source. Researchers found that, even though the soybean oil in a meal was completely replaced, the replacement of BSFL oil had no negative effects on growth performance, intestinal morphology, or the health of broilers (Kim et al., 2020; Schiavone et al., 2017, 2018). The BSFL oil can also enhance the broilers' intestinal morphology, barrier function, and plasma immune and antioxidant functions (Chen et al., 2022). Aquaculture feeds may also potentially use BSF oil as a source of fat (Dumas et al., 2018; Li et al., 2016; Xu et al., 2021). Dumas et al. (2018) reported that based on great growth performance and feed utilization BSFL meal and oil offered helpful nutrients to rainbow trout. BSFL oil had a less detrimental effect on fish responses and trial-measured variables than BSFL meal. The BSF oil enhances antioxidant capacity, controls lipid metabolism, and may help boost the immunity of fish (Xu et al., 2021). Additionally, BSFL fats can be employed in bakery products to impart tenderness, emit flavor compounds, provide mouthfeel, and reduce gluten structure. BSFL fat can work on these areas of baking production for a suitable application in bakery items (Dayrit, 2015; Delicato et al., 2020; Marangoni & Narine, 2002; Oonincx et al., 2015). Moreover, lipid extraction (defatting) from the BSFL is one of the important steps for biodiesel production.

4.4 Biodiesel

Due to its high oil content (35–40%) (He et al., 2022), BSFL holds potential as a viable source for biodiesel production. The presence of significant levels of both saturated and unsaturated fatty acids within BSFL contributes to approximately 70% of extractable oil, which can be further converted into biodiesel through transesterification (Mohan et al., 2023). Moreover, the engineering advantages of BSFL, including rapid proliferation that facilitates the conversion of food waste into lipids, increased lipid storage due to a lengthy larval development period, and self-separation from organic waste, offer promising prospects for biodiesel synthesis (Park et al., 2022). Notably, BSFL has demonstrated the ability to produce 94% of its biodiesel through non-catalytic transesterification, distinguishing it from the predominantly catalytic transesterification process employed for first-generation biodiesel production. By using less energy in the production process, biodiesel production is more environmentally friendly (Mohan et al., 2023).

For the production of biodiesel from BSFL, firstly washed and inactivated BSFL is dried, after oil extraction (solvent: hexane, petroleum ether, etc.), the excess solvent is removed (evaporation), purification steps may be applied (removing of water, pectin, phospholipids, and other impurities), and biodiesel is produced from BSFL oil by the selected method (reaction, evaporation, separation, and washing). Biodiesel production from BSFL from food waste by performed different techniques, such as non-catalytic transesterification (Jung et al., 2022), direct transesterification (Nguyen et al., 2018a), transesterification (Park et al., 2022), two-step method (acid-catalyzed esterification of and alkaline-catalyzed transesterification, Li et al., 2011a). The extraction of biodiesel from BSFL was mainly performed by the transesterification method (Kamari et al., 2020; Park et al., 2022). In the two-step procedure, BSFL fat was first esterified by an acid catalyst, due to its high acid value before being transesterified into biodiesel using an alkali catalyst (Mohan et al., 2023). For the enzymatic transesterification method, generally lipase enzyme was used (Nguyen et al., 2017 and 2018b; He et al., 2022). The single-step direct transesterification process offers several advantages, compared to the two-step technique. These advantages include high selectivity, easy recovery, minimal wastewater generation, reusable catalyst, thermal stability, and gentle treatment conditions (Su et al., 2019). In this process, lipid extraction and transesterification occur simultaneously in a single step, resulting in reduced energy consumption and shorter treatment times. Non-catalytic transesterification is an eco-friendly application that does not need chemical applications (Mohan et al., 2023).

The biodiesel yields depend on the organic substrate (food wastes, manures, etc.), lipid extraction methods (solvent extraction, enzymatic transesterification, ultrasound or microwave applications, etc.), production techniques (two-step process, enzyme (biocatalyst)-catalyzed transesterification, direct transesterification, non-catalytic transesterification) and conditions (solvent ratio, temperature, time, catalyst, catalyst concentration, catalyst to solvent ratio, etc., Mohan et al., 2023). The biodiesel yield of BSFL ranged between 48.46% (lipid extraction method: ultrasonic extraction, solvent: n-hexane, 1:8 methanol: H_2SO_4, (v:v), 55 °C for 60 min, Leong et al., 2016) and 98.45% (Lipid extraction method: enzymatic transesterification with methanol, Solvent: Petroleum ether, 1:3 methanol: Lipase (v:v), 25 °C for 8 h, He et al., 2022). The biodiesel yield of BSFL was generally found higher than 93% (He et al., 2022; Ishak et al., 2018; Jung et al., 2022; Kamari et al., 2020; Leong et al., 2021; Li et al., 2011a, 2015; Nguyen et al., 2017, 2020; Su et al., 2019; Wong et al., 2019, 2020a, 2020b; Zheng et al., 2012a).

The physicochemical properties of biodiesel from BSFL were reported as density: 843–895 kg/ m^3, viscosity: 2.7–5.96 mm^2/s, moisture content: 0.0003–500 mg/kg, sulfur content:0.0002–0.12%, ester content: 84.3–99.5%, acid value:0.2–1.1 mg KOH/g (He et al., 2022; Jung et al., 2022; Li et al., 2011a, 2011b; Nguyen et al., 2017, 2018b, 2020; Park et al., 2022; Su et al., 2019; Wang et al., 2017; Zheng et al., 2012a, 2012b).

Utilizing BSFL, which is recognized as one of the fastest growing and most promising insect species, is strongly recommended for the production of high-fat fifth-generation bioenergy. (Mohan et al., 2023). Furthermore, the high biodiesel yield of BSFL formed on food waste is important in terms of eliminating food waste and offering environmentally friendly biodiesel technology. The produced biodiesel from BSFL has to meet the standards of the EU (Acid value $<$ 0.50 mg KOH g^{-1} fuel and sulfur content: 10.0 mg sulfur kg^{-1} fuel) or the relevant country, otherwise, extra purification processes must be applied (Park et al., 2022).

4.5 Chitin and chitosan

Many industries use chitin (carbohydrate polymer) and its derivatives such as chitosan (deacetylated derivative) including the food, cosmetics, pharmaceutical, and textile industries. For this reason, chitin and its derivatives have a high economic value (Gortari & Hours, 2013). Large crustaceans, mollusks, crabs, insects, and small crustaceans are ecologically and economically efficient chitin sources. Representatives of domesticated and reproductive invertebrates can be a new and promising source of raw materials, especially since BSF contains a chitinous exoskeleton (Antonov et al., 2019). Chemical methods (demineralization, deproteinization, and deacetylation), enzymatic hydrolysis, and the use of eutectic solvents are the methods used for extraction of the chitin and chitosan from the BSFL. The chemical processes are generally used in industrial applications on crustaceans; however, it has been researched to improve the procedure for isolating and purifying chitin from BSFL and transforming it into its more useful derivative, chitosan which has a variety of uses, including the treatment of wastewater and the creation of bioactive coatings (Elieh–Ali–Komi et al., 2016). When compared to crustaceans, chitosan yields from BSFL were found to be lower, making the technique less economically viable, until it can be modified to produce a greater yield (Hahn et al., 2020).

The chitin content of BSFL can exhibit variations influenced by factors such as the insect's developmental stage and its diet. The chitin content of BSFL, pre-pupa, puparium, and adult has been reported as 3.2%, 3.1%, 14.1%, and 2.9% (db) (Wang et al., 2020). The chitin content of BSFL and pre-pupae was also reported as 6–7% (Spranghers et al., 2017) and 9% (db) (Caligiani et al., 2018).

For chitin extraction from the BSF, the defatting process has to be applied as a first step due to the high fat content of the BSFL. In order to prevent pigmentation, non-pigmented raw materials (fifth instar larval membranes) have to be used. Chitin extraction can be accomplished by removing macro and micronutrients (fat, protein, and minerals) and deacetylation (Caligiani et al., 2018; Khayrova et al., 2019). Defatting which is performed using an organic solvent is a simple process, even though deproteinization is more difficult. Alkali extraction is the most used method for the separation of proteins from chitin (Caligiani et al., 2018). When the studies are examined, it is seen that these processes are applied in different orders. Additionally, Hahn et al. (2022) reported that, in order to improve the chitin lightness and purification level by removing redox-sensitive and color-intensive impurities, primarily catechol molecules, bleaching treatment can be applied as a final step of chitin extraction from BSF pupal. The chitin yield strongly depends on the extraction method.

The chitin extraction from BSFL shows great promise, but several challenges and opportunities for improvement remain. As a result, since chitin and chitosan are adaptable substances that can be employed in a variety of industries, including food, medicine, and cosmetics, further research into the potential applications of BSFL is still necessary (Bessa et al., 2020; Kumar, 2000). The current limitations, including scale-up issues, cost-effectiveness, and downstream processing have to be studied. Moreover, optimizing extraction protocols, developing novel purification methods, and exploring value-added applications for chitin derivatives have to be focused on.

4.6 BSF frass

Many insect species can be used as a valuable fertilizer to replace chemical equivalents (Čičková et al., 2015; Menino et al., 2021). As an organic fertilizer, BSF frass (by-product from BSF rearing) is gaining popularity all over the world, due to its high nutrient amount, especially mineral content (Beesigamukama et al., 2020; Lalander et al., 2015). Examples of BSF frass as a fertilizer in plants such as lettuce (Kebli & Sinaj, 2017), onion (Zahn & Quilliam, 2017), basil and sudan grass (Newton et al., 2005), corn (Alattar et al., 2016), ryegrass (Kebli & Sinaj, 2017; Menino et al., 2021) and maize (Beesigamukama et al., 2020). However, the composition of BSF frass varies depending on the growing medium, so detailed studies are needed (Menino et al., 2021).

BSF frass is a rich source of organic matter, macroelements (N, P, and K), and microelements (Zn and Cu) (Kebli & Sinaj, 2017; Menino et al., 2021). In a study in which BSF frass was mixed with soil at different rates (0–150%) and used as a fertilizer in the development of ryegrass, the highest yield was observed in the sample with the highest percentage of BSF frass. The researcher reported that the combination of BSF frass with N fertilizer was promising; the addition of the BSF frass to the soil improved the K, P, and Mn concentrations, depending on the amount. For this reason, BSF frass could be added to soils with poor mineral composition (Menino et al., 2021). In another study, it was observed that, in comparison with maize treated with mineral fertilizer (urea), BSF frass-fertilized corn exhibited the tallest plants and maximum chlorophyll concentrations (Beesigamukama et al., 2020). In addition, scientists reported that BSF frass has a high nitrogen fertilizer equivalent (> 100%), which suggested that it can be a useful replacement for mineral nitrogen fertilizers.

As a result, BSF frass is regarded as an effective organic fertilizer thanks to its mineral content. In the studies, the highest yield was generally attained at the highest BSF concentrations, where BSF was employed as a fertilizer. The need for chemical fertilizers can be decreased by using BSF as an organic fertilizer. Moreover, the sale of these by-products can generate additional income for insect farms and reduce the cost of fertilizers for farmers. Furthermore, it matters what substrate the BSF is made from and more details are also related to the performance of BSF frass on crop growth, yield, nutrient uptake, and use efficiency compared to other fertilizers.

5 Future perspectives and conclusion

BSFL offer a promising solution to address the global food security challenge and environmental concerns. With the world's population projected to exceed 9.7 billion by 2050, traditional livestock farming and agricultural practices are becoming increasingly unsustainable. BSF farming has the potential to produce valuable goods with the least amount of negative environmental impact, making it a sustainable and environmentally friendly solution for waste management and pollution reduction. In order to effectively address the problems associated with organic waste and its effects on the environment in both urban and rural areas, BSF farming must uphold best practices and encourage responsible waste management. The use of BSFL as a source of protein and nutrients, reared sustainably on organic waste materials, presents a more efficient and eco-friendlier alternative. Their rapid growth, low environmental impact, and ability to convert organic waste into valuable products make them a sustainable choice for animal feed, fertilizer, and even biodiesel production. However, successful implementation requires optimization of various factors, including substrate selection, moisture content, temperature, and larval density. Proper pre-treatments and processing techniques are also essential to preserve the nutritional value and quality of the final products derived from BSFL. Ensuring safety and adhering to regulations are paramount to gain consumer acceptance for human consumption and expand the market potential of BSF-derived products. By integrating BSFL into the circular economy and promoting a shift toward sustainable food systems, we can enhance food production while mitigating climate change effects and conserving resources. Further research, investment, and collaboration are needed to maximize the efficiency and effectiveness of BSF production systems and unlock their full potential in supporting global food security and environmental sustainability. Besides that, waste management can also be enhanced by the sustainable and multipurpose uses of BSFL, which can be fueled by cutting-edge technologies and research methodologies. To realize the full potential of BSF farming in the future, a multidisciplinary approach incorporating automation, biotechnology, circular economy principles, and regulatory cooperation will be necessary. As we continue to explore and optimize strategies for enhancing the bioconversion rate and improving end products from BSF treatment, this innovative approach holds great promise for a more sustainable future.

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