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Insect protein: A pathway to sustainable protein supply chains, challenges, and prospects

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ABSTRACT

Insect protein holds promise in the global search for a sustainable protein supply chain, offering potential solutions to the challenges of conventional protein sources. This review explores the three pillars of sustainability – economic, environmental, and social – in the context of insect protein. Economically, insect protein is valued for its feed conversion and nutritional benefits in animal diets, offering a cost-effective alternative to conventional protein sources. Environmentally, insect farming presents a lower carbon footprint and reduced land and water usage compared to livestock production. However, concerns over the presence of heavy metals and bio-accumulates in the insect protein highlight the need for careful monitoring and safety standards. Socially, the widespread adoption of insect protein depends on overcoming regulatory hurdles and ensuring robust legislation to guarantee product safety, quality, and consumer acceptance. The review addresses critical barriers such as scaling production, developing efficient protein extraction technologies, and navigating complex regulatory framework. Insect protein shows strong potential to enhance global food security and promoting environmental sustainability, yet overcoming these challenges will require continued research, technological innovation, and cross-sector collaboration. By addressing these gaps, insect protein can play a crucial role in building more sustainable protein supply chain for both food and feed production.

1. Introduction

The escalating world demand for protein, coupled with the global sustainability challenges confronting traditional protein sources [1–5], has prompted the exploration of alternative sources like insect meal [6]. Insects are increasingly favoured as an alternative protein source due to their potential to mitigate future protein shortages and their minimal environmental footprint [7]. Compared to traditional animal farming, insect farming offers numerous advantages, such as reduced feed needs, reduced greenhouse gas emissions, smaller land usage, and quicker reproductive cycles [8]. Studies have demonstrated the feasibility of using insect meals as substitutes for soybean and fish meal in poultry

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diets, highlighting their potential value in the feed industry [9,10]. While the current production volumes of insect meal are relatively modest in comparison to other protein sources such as fish meal and soybean meal, there is potential to ramp up production, thus enhancing the accessibility and reliability of insect meal in the market [11].

The food and feed sectors of the insect business are predicted to be worth billions of dollars, driven by rising demand for alternative protein sources and the growing acceptance of insect-based diets [12,13]. Market research for black soldier fly larvae (BSFL), for instance, includes evaluating their production efficiency, nutritional composition, and potential applications in a wide range of industries, including animal feed, aquaculture, and even human consumption [14]. BSFL offer diverse opportunities across many industries, from animal feed, aquaculture, and potentially [15]. Additionally, BSFL exhibits efficiency in converting organic waste into edible biomass, presenting opportunities for waste management and the promotion of sustainable feed production, as observed by Mahmood et al. [16], and Kinasih et al., [17]. It was found that BSFL could reduce 77.0–96.1 % (by weight) and 72.8–89.0 % (by volume) of biowaste, providing a sustainable waste management solution, particularly in urban and rural areas [16]. Additionally, Kinasih et al. [17], demonstrated an efficient growth of BSFL on organic wastes such as horse manure, vegetable scraps, and tofu dregs. Overall, the potential for insects as protein alternatives is vast globally, driven by the demand for sustainable protein sources and the potential for market expansion and scalability.

By integrating insects into the circular economy, the industry has the potential to reduce waste, enhance resource efficiency, and foster a more sustainable and resilient food system [18]. Furthermore, the advancement of innovative insect manufacturing methods and procedures can play a crucial role in reducing waste generation throughout the supply chain, promoting a more sustainable and circular approach [19].

2. Insect meals as alternative energy and protein sources

Rearing insects as alternative sources of energy and protein has many advantages. Besides being highly nutritious with a high protein content (35 – 61 %), they are also easily reproduced, offer a better feed conversion ratio, and produce lower carbon footprints [20,21]. Moreover, insects can feed on various organic matter and transform it into valuable food and feed resources. The diversity of side-stream resources for insect production can promote a sustainable use of resources, and the increasingly important concept of circular economy. The use of these side-stream resources, however, may be limited by the legislation governing the quality and safety requirements of insects produced.

The legislative issues regarding insect production will be discussed in a later section of this review. In the EU legislation (EC Regulation No. 893/2017), seven insect species, to some extent, are permitted to be used as animal feeds. They are BSFL, common housefly (*Musca domestica*), yellow mealworm (*Tenebrio molitor*), lesser mealworm (*Alphitobius diaperinus*), house cricket (*Acheta domesticus*), banded cricket (*Gryllodes sigillatus*) and field cricket (*Gryllus assimilis*). These insects are notably high in protein and fat content [22]. For pigs and poultry, whole insect and insect-derived fats are allowed in the feeds, given that the insects are strictly fed with diets of vegetal origin. Insect-processed proteins, however, are still prohibited. At present, various regulatory bodies are exploring the possibility of fully authorising the use of insect proteins in pig and poultry feeds.

2.1. Variation in the nutrient composition of insect meals

The nutritional values of insects greatly vary in species, diets (growth substrates), developmental stages, and environment [21,23]. These variations may lead to many challenges, particularly for large-scale production and application. Nevertheless, despite the variability in the nutritional values, insects possess great potential in a wide range of applications – especially as animal feeds, as reported in numerous studies [22,24]. A recent meta-analysis has revealed that various growth substrates affect the growth efficiency and nutritional values of BSFL [23]. BSFL fed with animal feed showed an average of 36 % shorter time of rearing, 30 % better feed conversion ratio, and 38 % higher crude protein (CP) content.

Temperature and humidity are among the crucial abiotic factors affecting the growth, development, mating, and oviposition of insects [21]. Due to their poikilothermic nature, many insects can tolerate a wide range of climatic conditions. Several studies have reported a 30 % higher body weight for insects raised at a higher ambient temperature (27 – 35 °C), compared to a lower temperature (<25 °C) [25,26]. The time for egg eclosion in BSFL was reported to decrease with increasing relative humidity [27]. Therefore, inconsistencies in the yield and nutritional quality of insects can be expected with varying climatic conditions. Barragan-Fonseca et al. [28], reported that BSFL's CP content (37–63 % DM) and fat content (7–39 % DM), emphasizing the profound effects of diet and environmental condition. The study highlighted chitin's variability with developmental stage, underscoring its influence on digestibility and the necessity for species-specific optimization in feed applications. Similarly, Józefiak et al. [29], reported CP and fat content of 38–60 % DM and 9–26 % DM, respectively, for BSFL, while mealworms exhibited higher fat content (31–43 % DM) and comparable CP levels (47–60 % DM). These studies collectively demonstrate that nutritional quality is intricately linked to life stage, diet composition, and rearing conditions.

Spranghers et al. [30], further explored BSF prepupae, revealing CP levels of 39.9–43.1 % DM, fat content of 21.8–38.6 % DM, and ash content ranging from 9.6 to 19.7 % DM, with chitin content varying between 5.6 and 6.7 % DM. Substrate type and larval stage were found to significantly influence these parameters, highlighting the critical role of environmental management in achieving consistent nutritional profiles. Bbosa et al. [31], extended these findings to four insect species–BSF, *Calliphora vomitoria* (blue calliphora fly), *Acheta domesticus* (house cricket), and *Ruspolia nitidula* (grasshopper). The authors found that the CP content ranged between 40.79 and 64.90 % DM, fat from 0.67 to 46.29 % DM, fiber levels of 5.07–16.61 % DM. Such variations were attributed to diet, substrate, and harvesting season, further emphasizing the need for tailoring rearing strategies. House and field crickets (Acheta domesticus and Gryllus bimaculatus) exhibited CP contents of 71.7 % and 60.7 %, with fat levels of 10.4 % and 23.4 % DM, respectively [32]. Fiber content ranged from 4.6 to 10.0 % DM, influenced by developmental stage and dietary inputs. Similarly, Bawa et al. [33] reported house cricket CP levels reaching 76.19 %, with fat and fiber contents of 8.9–43.9 % and 3.7–7.5 %, respectively. Notably, protein-rich diets resulted in reduced fat deposition and enhanced protein levels, underscoring the role of nutritional formulations.

Yoo et al. [34], characterized *Tenebrio molitor* (yellow mealworm) as a promising protein source with CP content of 46–52 % DM, fat content of 25–35 % DM, and crude fiber at 6.1 % DM. The nutritional composition was influenced by larval stage, feed, and processing methods, while the low chitin content had minimal impact on digestibility. Collectively, these findings highlight the necessity of species-specific optimization, particularly for insects destined for feed and food applications, to maximize yield, nutritional value, and consistency.

2.2. Feeding values of insect meals

One of the most important applications of insects is in animal feeding, particularly poultry and pigs. The uncertainty in the global supply of animal feed has urged the need for an alternative feed ingredient to sustain the livestock industry. In poultry nutrition, high protein, and fat content in insect meals can complicate the diet formulation, especially when attempting to replace a substantial amount of soybean meal and vegetable oil in the diet. Insects have been fed as whole full-fat meals [35], defatted protein meals [24], and oil extracts [36]. Many studies have reported the benefits of feeding insect meals to poultry [36, 37] and even ruminants [38]. The nutritional values of BSFL have been extensively studied. The CP content of BSFL ranged from 35 to 61 % and the fat content ranged from 7 to 42 %. The BSFL also contains high concentrations of lauric and palmitic acids. Other reported nutrient contents include methionine (0.08 − 0.90 %), threonine (0.22 − 2.26 %), calcium (1.21 − 4.39 %), and phosphorus (0.74 − 0.95 %) [22]. When fed with an unprocessed whole BSFL, the birds showed a higher preference over the regular feed [39]. The same study also concluded that the chickens can consume up to 30 % unprocessed whole BSFL of their voluntary feed intake, without adverse effects on growth performance and feed conversion ratio (FCR). A poor FCR has been reported with a high inclusion level of defatted BSFL [24]. On the contrary, dietary BSFL oil improves FCR, the tissue deposition of medium-chain FA, and serum antioxidant capacity in broiler chickens [40].

The CP of mealworm meal ranged from 27 to 54 % and fat content ranged from 4 to 34 %. Mealworm meal is rich in unsaturated FA with a high concentration of n-6 FA. Among significant FAs present in mealworm meal are oleic acid (C18:1 *cis*-9; 43.8 g/100 g FA), linoleic acid (C18:2 *cis*-9, 12; 30.2 g/100 g FA), and palmitic acid (C16:0; 16.4 g/100 g FA) [36]. A diet containing 4 % mealworm meal improved the FCR of broiler chickens in the starter phase. In the same study, no effect on the meat quality was observed in all treatments [22]. Benzertiha et al. [36], reported no adverse effects on growth performance or nutrient digestibility on broilers fed with 5 % mealworm oil. In the same study, the birds also showed lower hepatic fat content and higher deposition of n-6 and n-3 polyunsaturated fatty acids (FA) in the breast tissue, as compared to the birds fed with 5 % poultry fat and 5 % palm oil.

Other insect species such as house cricket, lesser mealworm, and superworm are also highly valuable in terms of their nutritional values [41,42]. Nevertheless, the reports on the feeding values of these insects are limited. House crickets contain (on dry matter (DM) basis) a high CP content (55 − 67.2 %), though some lower values (<30 %) have also been reported [42]. They are particularly high in leucine and lysine, which are comparable to the mealworms [42]. They also contain 9.8 − 22.4 % fat. The major fatty acids found in house cricket include linoleic (30 − 40 %), palmitic (24 − 30 %), oleic (23 − 27 %), and stearic acids (7 − 11 %). They also contain high amounts of vitamin A, E, C, and B complex [43]. Compared to BSFL and mealworm, the study on feeding chickens with whole full-fat, defatted protein meal or oil extracts of house crickets is limited. There are a few studies done on ruminants [44, 45]. Most studies focus on the immunomodulatory potential of cricket chitin. For instance, Lokman et al. [46], reported that broilers fed with 0.05 % cricket chitin showed a significant improvement in growth performance and carcass quality.

3. BSFL

BSFL stands out as one of the most extensively researched insect proteins, with a wealth of data and findings from previous studies. Hence, this section aims to present a comprehensive overview of recent research endeavours, exploring the applications of BSFL-derived products and the challenges inherent in BSFL research.

Utilizing BSFL for organic waste valorization represents a promising application within the circular economy framework [47]. Organic waste generated by plantations or animal farms serves as prime feedstock (substrate) for BSFL, leading to the production of biomass suitable for animal feed. Moreover, the frass, or excrement, produced by BSFL serves as a valuable biofertilizer for plantations [48]. This symbiotic process establishes a sustainable and resource-efficient cycle, contributing to environmental conservation efforts [49].

The utilization of BSFL-based technology enables the extraction of various valuable products from organic waste streams. These products include feed materials rich in protein, fat, biodiesel, chitin, and biofertilizers [50,51]. Consequently, BSFL rearing emerges as a sustainable and economically viable process, fostering resource recovery and creating new opportunities for both the industrial sector and entrepreneurs [52].

3.1. BSFL as a sustainable protein alternative for animal feed

One of the most useful components of BSFL is its high protein content which makes it a promising ingredient in animal feed to replace expensive protein sources like fish meal. BSFL has been explored in feed for fish, prawns, frogs, ruminants, and pets as shown in Table 1. BSFL is a suitable nutrient alternative to fish meal in Siberian sturgeon (*Acipenser baerii*) nutrition with a replacement of 10–30 % without any differences in specific growth rate and weight gain [53]. Incorporation of 10–30 % BSFL into a diet for red hybrid tilapia (*Oreochromis* spp.) fingerlings did not cause any adverse effect on growth and it increased crude protein and fat composition in fish meat [54]. Siamese fighting fish (*Betta splendens*) fed with 13 % BSFL had improved growth performance, blood parameters, and liver and intestine morphology thus revealing its promising potential to be used as an alternative diet for ornamental freshwater fish [55]. Incorporating 5–10 % BSFL in the diet did not significantly affect ($p > 0.05$) the growth in Atlantic salmon (*Salmo salar*) instead it can modulate the immune responses in Atlantic salmon reared at a large scale under farm-like conditions [56]. Nile tilapia fry (*Oreochromis niloticus*) fed with a diet containing 75 % BSFL not only improved growth, feed efficiency, liver and intestinal organs, and enhanced nitrate for increased natural productivity but also reduced 30 % of feed cost leading to 4 % higher economic returns [57].

He et al. [58], concluded that the replacement of commercial feed up to 50 % with fresh BSFL could be feasible for Pacific white shrimp (*Litopenaeus vannamei*) farming in terms of growth performances, digestive enzyme activities, intestinal histology, and antioxidant enzymes. BSFL meal could be used up to the level of 22.5 % to substitute fish meal in the diet for *Litopenaeus vannamei* growth without any adverse effects [59]. Growth performance, non-specific immune responses, and antioxidant enzyme activity of *Litopenaeus vannamei* fed with a BSFL-included diet were significantly improved [60]. The growth performance (weight gain, FCR, and specific growth rate) of Pacific white shrimp was significantly improved with increasing inclusion of the BSFL (4.5 − 10.5 %) while health performance was not significantly altered [61]. Pacific white shrimp fed with 5 and 10 % BSFL diets exhibited significantly higher body weight, with the 10 % diet achieving the highest weight and lowest FCR, while all treatment groups showed reduced *Vibrio* spp. Counts in the hepatopancreas and intestines, alongside improved immune responses and survival rates compared to the control diet [62]. The experimental diets with BSFL inclusion did not negatively affect survival rates, growth rates, and welfare status of giant freshwater prawn (*Macrobrachium rosenbergii*) post-larvae [63]. A diet with 20 % BSFL promoted lipid synthesis and lipolysis, while a 30 % BSFL diet weakened β-oxidation, glycolysis, and unsaturated fatty acids synthesis, which may negatively affect the growth performance and body composition of *Litopenaeus vannamei* [64]. Fish meal can be fully replaced by BSFL meal in shrimp with no negative effect on growth but it is only economically feasible if replacement percentages are kept at 19.74 % [65].

BSFL with high protein and fat contents and a rich source of vitamins and minerals has the potential to reduce the cost of chicken feed formulations by partially replacing soybean and/or fish meals [66]. Bovans White laying hens fed with a 20 % live BSFL diet could promote sustainability in the egg industry, and it would only be economically sound if BSFL could be bought in bulk for less than 40 % of the cost of the concentrate [67]. A low level of BSFL (10 %) improved live weight and average daily gain in male broiler chickens (Ross 308) and there were no significant effects ($p > 0.05$) on the haematochemical parameters or histological findings [68]. BSFL can cost-effectively replace fish meals by up to 20 % without compromising the growth performance of the improved indigenous chicken thus potentially reducing the total feed cost while maintaining optimal production and eventually reducing the cost of meat and egg products [69]. BSFL meal can substitute up to 540

Table 1
Summarized the usage percentage and effects of BSFL in animal diets.

BSFL meal percentage as a protein source	Targeted species	Effects	References
10–30 %	Siberian sturgeon	Increase growth and feed utilization (as compared to 5 % replacement) but no effect on feed digestibility	[53]
10–30 %	*Oreochromis* spp	Did not impair growth performance, crude protein and crude fat of fish meat were significantly higher in fish fed with higher BSFL percentage	[54]
13 %	*Betta splendens*	Improved growth performance, blood parameters, and liver and intestine morphology	[55]
5–10 %	Atlantic salmon	A 5 % BSFL diet improved immune responses in Atlantic salmon reared at a large scale under farm-like conditions.	[56]
25–100 %	*Oreochromis niloticus*	Feed with 75 % BSFL improved growth performance, feed efficiency and economic returns	[57]
0–100 % fresh larvae	*Litopenaeus vannamei*	At least 50 % of commercial feed could be replaced with fresh BSFL without significant adverse effects on growth performance and survival rate, digestive enzyme activities, and antioxidant enzyme activities of *L. vannamei*	[58]
22.5 %	*Litopenaeus vannamei*	No significant difference on the specific growth rate, weight gain, survival rate, feed efficiency, and protein efficiency ratio of white shrimp	[59]
30 % BSFL + 70 % reference diet	*Litopenaeus vannamei*	Growth performance, non-specific immune responses and antioxidant enzyme activity of shrimp fed with BSFL included diet were significantly improved.	[60]
4.5, 7.5 & 10.5 %	*Litopenaeus vannamei*	Growth performance (weight gain, feed conversion ratio, and specific growth rate) of shrimp was significantly improved with increasing inclusion of the BSFL while health performance was not significantly altered	[61]
2, 5 & 10 %	*Litopenaeus vannamei*	Shrimp fed with 5 and 10 % BSFL diet had significantly increased body weight and reduced FCR while all 3 treatments decreased hepatopancreatic and intestinal *Vibrio* spp. Count, and improved immune parameters and survival rates	[62]
3 & 20 %	Giant freshwater prawn	The experimental diets did not negatively affect survival rates, growth rates and welfare status of *M. rosenbergii* post-larvae	[63]
10, 20 & 30 %	*Litopenaeus vannamei*	A 20 % BSFL diet promoted lipid synthesis and lipolysis, while a 30 % BSFL diet weakened β-oxidation, glycolysis and unsaturated fatty acids synthesis, which could possibly affect the growth performance and body composition of shrimp	[64]
0, 25, 50, 75, 100 %	*Penaeus vannamei*	Fish meal can be fully replaced by BSFL meal in shrimp with no negative effect on growth but it is not economically feasible	[65]
0, 10, 20 % ad libitum of live BSFL	Bovans White laying hen	Hens fed with ad libitum live larvae consumed less concentrate and gained more weight than all other treatments	[67]
0, 5, 10, 15 %	Male broiler chickens (Ross 308)	A low level of BSFL (10 %) improved live weight and average daily gain in male broiler chicken (Ross 308) and there were no significant effects on the haematochemical parameters or histological findings	[68]
0–20 %	Improved indigenous chicken (IIC)	The highest cost-benefit ratio was recorded for birds fed on a diet with 20 % BSFL without compromising the growth performance of the birds	[69]
0–100 %	Broiler chicken (Cobb500)	Substitution of up to 500 g/kg DM did not compromise growth performance parameters	[70]
0–100 %	Native chicken	Basal rations + 25 % fish flour + 75 % BSF flour can improve the performance of native chickens	[71]
0–100 %	ISA Brown layer chicks	The diet treatment with 100 % inclusion levels of BSFL showed the highest intra-species alpha diversity and richness. Diet types significantly influenced the abundance of the microbiota, but differences between the most abundant taxa were similar	[72]
3 & 5 %	Arbor Acres broiler chicks	BSFL diet (3 % and 5 %) has no negative effects on growth performance, red blood cell characteristics, blood lipid profiles, and nutrient excretion	[73]
36 %	Steer	36 % BSFL mixed with soyhulls and wheat middlings may be an effective protein supplement for beef cattle which consume low-quality forage	[75]
4 & 8 %	Pig	A diet with 4 % BSFL which replaced the fish meal significantly improved the meat quality of growing pigs while supplementation of 8 % black soldier flies had	[76]

(*continued on next page*)

Table 1 (*continued*)

BSFL meal percentage as a protein source	Targeted species	Effects	References
		positive effects on the growth performance of pigs	
25, 50, 75 & 100 %	hybrid pigs (crossbreeds of purebred Large White and Landrace)	BSFL diet significantly affected pig growth performance where carcass weight of pigs fed diets with BSFL meal replacing fish meal by 50, 75 or 100 % (w/w) was higher than control diet, and the highest carcass weight was observed in the 100 % BSFL meal replacement group	[77]
0, 5 & 10 %	Piglet	No overall significant differences in growth performance, nutrient digestibility, blood profile, gut morphology and histological features	[78]
75 & 150 g of live BSFL twice a day	Piglets (Pietrain x TN70)	Live BSFL did not negatively affect piglet growth, feed efficiency, energy efficiency, and faecal consistency	[79]
50 & 100 % live BSFL 50 & 100 % dried BSFL	*Rana rugosa* (Thai Frog)	All treatments do not affect the survival rate except for 100 % fresh BSFL. 50 % BSFL +50 % commercial feed significantly improved feed conversion, increased live weight, daily weight gain and frog's yield	[80]
5, 10 & 20 %	Beagle dog	BSFL meal and BSFL oil diets are well tolerated by dogs with no impact on physiology	[81]

g/kg in broiler chicken starter diets without compromising growth and feed utilization efficiency, with a resultant reduction in feed cost and increased marginal economic benefits [70]. Native chickens fed with basal rations with 25 % fish flour and 75 % BSFL flour had significant improvement in their growth performances in terms of feed consumption, body weight, and protein consumption [71]. Feeding ISA Brown layer chicks with a BSFL diet increased the species diversity and species richness of gut microbiota which could be exploited further to improve poultry health and nutrition [72]. BSFL was fed to broiler chickens at 3 % (starter period) and 5 % (grower-finisher periods) without adverse effects on growth performance, red blood cell characteristics, blood lipid profiles, and nutrient excretion [73].

BSFL was also evaluated for its potential to be used in ruminant feed. Astuti & Wiryawan [74] found out that BSFL can be used as a milk replacer, creep feed, fattening ration, and source of lactic acid bacteria probiotics for ruminant feed. A 36 % BSFL mixed with soyhulls and wheat middlings could be used as an effective protein supplement for beef cattle that consume low-quality forage [75].

A diet with 4 % BSFL which replaced the fish meal significantly improved the meat quality of growing pigs while supplementation of 8 % BSFL had positive effects on the growth performance of pigs [76]. The BSFL diet significantly improved pig growth performance, with pigs fed diets where BSFL meal replaced fish meal by 50, 75 or 100 % (w/w) showing higher carcass weights than other diets, and the highest carcass weight was observed in the 100 % BSFL meal replacement group [77]. There were no significant differences ($p > 0.05$) in growth performance, nutrient digestibility, blood profile, gut morphology, and histological features of piglets fed with 0–10 % BSFL diets [78]. Live BSFL fed to post-weaning piglets positively affects the behaviour while maintaining the growth performance [79].

Besides the economically important species mentioned above, BSFL has been tested in frog and dog diets. The diet comprised of 50 % fresh BSFL with 50 % commercial feed improved growth rate, FCR, weight gain, and frog yield thus it could be applied successfully in Thai frog cage production [80]. BSFL meal and BSFL oil diets are well tolerated by Beagle dogs with no impact on physiology [81].

3.2. Lipids and oil

The content of lipids in BSFL is usually higher than the nutrient requirement of the animal thus it may need to be removed or reduced before inclusion in the animal diet. Dairy cows fed with BSFL fat at different dosages (10 g/head/day & 100 g/head/day) lead to better indicators of pre-gastric digestion and increased milk production [82]. BSFL fat consists mainly of saturated fatty acids and thus may not be feasible as fish oil replacement, but it has the potential to be utilized in other food, feed, and fuel products [83]. BSFL oil has the potential to be used as an alternative oil ingredient in cosmetic products due to its anti-skin aging, whitening, and ultraviolet B (UV−B) protection properties [84]. Lauric acid which is a dominant component in BSFL lipids exhibits antibacterial, antifungal, antiviral, and anticancer properties which promote its applications in various industries such as pharmaceuticals, food and beverages, cosmetics, body care, soaps and detergents, plastics, and textiles [85].

3.3. Chitin and chitosan

Chitin, which is an indigestible substance, found in BSFL could increase eggshell thickness and microbiota diversity values of laying hens [86]. Chitin isolated from BSF pupal exuviae has the potential to be used as a heavy metal biosorbent with relatively high efficiency and good sorption properties [87]. The similarity of BSFL-derived chitin to commercial polymers makes them suitable for industrial and biomedical applications meanwhile chitosan obtained from the deacetylation of BSFL-derived chitin confers its antimicrobial properties [87]. Chitosan isolated and purified from BSFL was confirmed for its antioxidant activity [88].

4. Current challenges

The multifaceted applications of BSFL, particularly in organic waste valorization, underscore its potential as a key player in advancing circular economy principles [89]. Nevertheless, despite its promise, BSFL research faces several challenges that warrant further investigation and innovative solutions to fully harness its benefits and address existing limitations [90].

Insects are emerging as a prominent protein source in the food and feed industries, driven by the increasing demand for sustainable and environmentally acceptable alternatives [91,92]. The scale and value of the insect market will be influenced by consumer acceptability, regulatory advancements, and processing technology [7]. To facilitate the commercialization of insects, additional research and development efforts are necessary to refine production techniques, enhance processing protocols, and address consumer acceptance concerns [93].

4.1. Legislative issues regarding the use of insects as feeds

Bringing insects into the food supply chain will be inevitably subject to various legislations governing the production, processing, and distribution stages. Although there are increasing demands on the use of insects as alternative feed sources, the changes in policies and regulations are rather slow. In this regard, the European Union (EU) is leading in making a change – though with some limitations, compared to other regions. Therefore, the regulations and developments in the EU are referred to. In early 2000, the so-called "EU Feed Ban" was introduced by the EU authority in reaction to the BSE outbreak (EC Regulation No. 999/2001). Consequently, animal-source feeds including insect origin are not allowed for livestock feeding. As aforementioned, recent EU legislation (EC Regulation No. 893/2017) has permitted the use of seven insect species – to some extent, as animal feeds including aquaculture.

For pigs and poultry, whole insect and insect-derived fats are allowed in the feeds, given that the insects are strictly fed with diets of vegetal origin. Insect-processed proteins, however, are still prohibited. Insects are not specifically mentioned in most legislative texts, though animal protein is prohibited in animal feed. Fishmeal, however, is allowed in animal feed as per EC Regulation 142/2011. It is defined as a processed animal protein (PAP) derived from aquatic animals, except sea mammals [94]. At present, the European Commission is exploring the possibility of fully authorising the use of insect proteins in pig and poultry feeds. Imposing a strict feeding practice that prohibits the use of non-vegetal diets may hinder the prospects of a circular economy – i.e. valorization of waste streams for food production.

Many studies have reported the potential of using insects such as BSFL in organic manure and food waste composting, producing high-protein larvae meals [95]. Parodi et al. [96], concluded that BSFL showed a greater preference for manure than a mass-rearing diet. Feeding insects with animal-source ingredients is tightly regulated due to the concern about the hazard of prion diseases [94]. BSFL thrive on animal-source diets, with excellent growth and development parameters, high larval protein content, and favourable amino acid profile [23].

Insect producers and distributors must strictly adhere to the general principles and standards in food and feed safety, which are governed by legislations such as the General Food Law (EC Regulation No. 178/2002), Hygiene Package (e.g., EC Regulation No. 183/2005 on feed hygiene) and Novel Foods Legislation (e.g., EC Regulation No. 2015/2283). In addition, there are also several EU regulations governing the safety of animal feeds, including EC Regulation No. 1069/2009, EC Regulation No. 142/2011, EC Regulation No. 999/2001, EC Regulation No. 1137/2014, and EC Regulation No. 767/2009 [97].

Insect producers are also required to follow the hazard analysis and critical control point (HACCP) principles. Several categories of hazards are regulated for feed ingredients which include physical, chemical, and microbiological hazards [94]. Microbial and heavy metal contaminants are among the major concerns. The composition of the bacterial and archaeal gut community in BSFL is largely affected by the types of diets and their direct contact with sources with high bioburden [98]. The authors reported that the BSFL gut microbiota species richness and diversity were decreased when fed with chicken feed and grass cuttings, but remained stable for fruit/vegetables treatment. Nevertheless, the author has concluded that despite the large effect of diets on BSFL biomass, fresh substrates with low bioburden had no significant effect on the microbial gut communities. Among the core gut microbiomes in BSFL include *Actinomyces* sp., *Dysgonomonas* sp., and *Enterococcus* sp. The presence of some potentially pathogenic genera such as *Enterococcus*, *Staphylococcus*, *Pseudomonas*, *Campylobacter*, and *Klebsiella* in manure-fed larvae has raised a safety concern [99]. House fly is a well-known vector for *Campylobacter* spp. that can infect chickens and cause campylobacteriosis. Diener et al. [100], examined the bioaccumulation of heavy metals in BSFL fed with chicken feed, spiked with cadmium, lead, and zinc. They had observed an increase in the bioaccumulation of cadmium bioaccumulation by almost 3-fold; lead bioaccumulation remained below its initial concentration, while zinc bioaccumulation decreased with increasing zinc concentration. This study indicates the risk of heavy metal bioaccumulation by insects, stressing the need for a strict regulatory measure.

There are large disparities among different economic regions and countries in the regulation of insect production, despite the familiarity of entomophagy in some cultures. Despite the extensive scientific research, the lack of specific legislation by governments and differences across borders can complicate the marketability of insects. Many countries have yet to draft specific legislation pertaining to insects as food and feed. Many insect-based startup companies are affected by this circumstance, becoming a barrier to their growth. Lähteenmäki-Uutela et al. [101], have published a brief review of the global comparison in the regulations of insects as food and feed. The EU legislation on insects as food and feed has been extensive. However, there is a limitation for broader usage, especially the PAP. Defatting the whole insect – hence, a processed insect protein meal, is inevitable as the high-fat content in many insect species can complicate the diet formulation. A non-profit organization called the International Platform of Insects for Food and Feed (IPIFF) is actively promoting insects as food and feed sources through the engagement of various stakeholders. In the United States, insects are considered food by the Food and Drug Administration (FDA). Therefore, insect production must strictly follow good manufacturing practices in production, packaging, storage, and transportation. Insect producers can submit GRAS (generally recognized as safe) notice to the FDA for a review, which offers a faster route to market with a fraction of the cost [101]. In Canada, insects need authorization and pre-market assessment by the Canadian Food Inspection Agency. According to Lähteenmäki-Uutela et al. [101], BSFL is permitted as aquaculture and poultry feed in Canada. Thailand has established Good Agricultural Practices for Cricket Farm (Thai Agricultural Standard 8202-2017), which is governed by the FDA Thailand. As the world's largest cricket producer, this regulation is necessary to ensure the quality and safety of crickets for exports.

4.2. Scaling up the production

The insect farming industry encounters numerous challenges in optimizing production and expanding operations to meet the increasing demand for insect-based products. This involves increasing production volumes while maintaining product quality and sustainability. Li et al. [102], investigated genetic enhancement techniques in BSFL aiming to boost growth performance and protein content. They explored methods like selective breeding and genetic modification. Results revealed significant improvements in both growth rates and protein content, indicating the potential for enhanced biomass production. Barroso et al. [103], also delved into similar strategies by finding genetic manipulation to be promising in augmenting BSFL traits. Their findings underline the feasibility of genetic approaches in enhancing BSFL productivity, which could hold implications for sustainable protein production and waste management. The efficacy of automated rearing systems in scaling up insect production for feed was studied by Klunder et al., [104]. Their study emphasized the need for technological advancements to overcome production challenges, enhancing efficiency and scalability in insect farming. By evaluating automated systems, they found improved production rates and streamlined processes, indicating the potential of automation in addressing key hurdles in insect feed production. Likewise, Makkar et al. [105], investigated recent advancements in automated feeding systems for insect colonies, focusing on precision-controlled dispensers and robotic feeders. They discovered that using precision-controlled dispensers and robotic feeders significantly improved growth rates and overall productivity of insect colonies by optimizing their diets. Tomberlin et al. [106], explored advancements in robotics and artificial intelligence (AI) for automating labour-intensive tasks in insect farming, like sorting and cleaning. Their findings demonstrated that automation significantly decreased manual labour and operational costs, leading to enhanced efficiency and scalability in insect production and consequently improving its economic viability.

Recent research has shed light on the challenges facing insect farming, particularly in optimizing production and scaling up operations. Studies have provided valuable insights into addressing these challenges through genetic enhancement techniques, automated rearing systems, and advancements in robotics and AI. By implementing these strategies, insect farming can improve productivity, optimize diets for insects, and reduce operational costs, ultimately ensuring a more sustainable and economically viable future for insect-based products.

4.3. Heavy metals and bioaccumulants

BSFL fed on a high solid aquaculture wastes diet accumulated metals and micronutrients at levels that exceed regulatory limits especially heavy metals like cadmium [107]. Thus, it is important to carefully scan for those risks in new BSFL feed (highly concentrated or likely to contain high concentrations of chemicals or microelements) and the larvae feed on them to ensure safety. The type of organic substrates used in rearing BSFL should be thoroughly studied to minimize vertical transmission of pathogens which could be harmful to poultry and consumers [72]. Killing the BSFL (by blanching or freezing) significantly influenced the microbial load and the heavy metal content of the BSFL where blanching significantly reduced microbial contamination of the BSFL but only resulted in slightly lower heavy metal concentrations in the larvae [108]. Heavy metals such as Zn, Mn, Cr, Pb, Fe, Sn, and Cd which were bioaccumulating in the BSFL were found to be influenced by their feed although they were below legal limits [108,109].

Three main cross-reactive allergens, namely tropomyosin, arginine kinase, and myosin were found to be present in the BSFL samples through mass spectrometry, and their abundances were not influenced by their feed [108]. BSFL can be reared on former food products with traces of packaging materials with no adverse effects on their growth or survival but bio-accumulation was observed for most of the tested contaminants especially mineral oils and cadmium at concentrations below the respective legal limits in the EU [110]. Substrates used to feed the BSFL could pose a potential risk of pathogens that endanger productivity but the introduction of specific beneficial microorganisms in the process may suppress the diseases and create a synergistic biome for the larvae [111]. Contaminants such as mycotoxins, heavy metals, pesticides, and pharmaceutical compounds, were found to not affect the survival rate, growth rate, and biomass gain of BSFL except for the pesticides cypermethrin and tebufenozide. Although BSFL does accumulate heavy metals like cadmium, arsenic, and lead instead of accumulating pesticides, pharmaceuticals, and mycotoxins, BSFL either excreted them or reduced their concentrations in the residual frass [112].

4.4. Technological challenges

Addressing the challenge of devising efficient protocols for protein extraction from insects with minimized energy expenditure and preservation of protein integrity constitutes a significant endeavour. Diverse extraction methodologies encompassing mechanical, chemical, and enzymatic approaches have been investigated [113]. Mechanical disruption techniques encompass physical processes like grinding, crushing, or pressing to dismantle insect tissues and liberate proteins [114]. Such mechanical extraction methods frequently demand substantial energy input and may induce protein denaturation owing to shear forces [115]. Chemical techniques employ solvents or reagents to dissolve or denature proteins, thereby aiding their extraction from insect biomass [116]. These methods may necessitate the use of hazardous solvents, presenting potential environmental and health hazards. Furthermore, certain chemicals could modify protein structure, potentially impacting its functionality [117]. Enzymatic approaches entail employing specific enzymes to catalyse the hydrolysis of proteins into smaller peptides or amino acids, facilitating their liberation from insect tissues [118]. However, such extraction methods may incur time and cost constraints due to the requirements of specific enzymes. Additionally, enzymes might exhibit restricted stability and efficacy under particular conditions [117].

5. Future direction of insect protein

Over the past few years, the utilization of insect protein has emerged as a sustainable and nutritious alternative to conventional protein sources, driven by the escalating global demand for sustainable food and feed production. Insects offer a promising solution owing to their high nutritional value, efficient conversion of feed into protein, and minimal environmental footprint. Expanding the repertoire of insect species and product diversity is essential for advancing the development and utilization of insect protein. While species like BSFL, mealworms, and crickets have been extensively studied, there exists untapped potential for exploring other insect species.

Scaling up production and enhancing efficiency is a pivotal challenge in insect protein production. Efforts should focus on developing efficient mass-rearing systems, such as vertical farming methods and automated monitoring systems, to increase yields and reduce production costs. Advancements in feed formulations and insect genetics hold promise for augmenting production efficiency further. Technological innovations in extraction are crucial for maximizing the utilization of insect biomass. Research endeavours should prioritize the development of novel extraction techniques such as high-pressure processing, ultrasound-assisted extraction, and enzymatic hydrolysis. These advancements can facilitate the production of high-quality insect protein isolates and concentrates suitable for various food and feed applications.

Addressing regulatory and consumer acceptance issues is imperative for the mainstream adoption of insect protein. Establishing clear regulations and standards for insect farming, processing, and labelling is crucial to ensure food and feed safety and quality. Educational campaigns and marketing initiatives are essential for raising awareness and promoting the benefits of insect protein, thereby fostering consumer acceptance and adoption.

Integration into the circular economy and sustainable food and feed systems represents another avenue for advancing insect protein utilization. Utilizing organic waste streams and by-products as feed sources for insect rearing can reduce food waste and promote resource efficiency. Moreover, integrating insect farming with other agricultural and aquaculture systems can create synergies, contributing to the overall sustainability of food production systems.

Ultimately, the future of insect protein holds immense potential for addressing global challenges related to food security, environmental sustainability, and public health. By embracing these future directions, including species diversification, production scaling, technological innovation, regulatory compliance, and integration into sustainable food systems, insect protein stands poised to emerge as a mainstream and viable protein source for the future. Collaboration and concerted efforts across various sectors will be crucial for realizing this vision and achieving the full potential of insect protein.

6. Conclusion

In conclusion, the trajectory of insect protein offers immense promise in addressing global challenges related to food security, environmental sustainability, and public health. By exploring novel insect species, expanding production capabilities, improving processing methodologies, addressing regulatory and consumer acceptance concerns, and integrating insect farming into sustainable food networks, insect protein is positioned to become a pivotal and sustainable protein source in the years ahead. Sustained efforts in research, innovation, and partnerships across academia, industry, and government sectors will be essential to realize this vision and fully harness the potential of insect protein.

CRediT authorship contribution statement

Azizah Mohamad: Writing – original draft, Methodology, Data curation, Conceptualization. **Chun Keat Tan:** Writing – review & editing, Conceptualization. **Nor Nadiah Abdul Karim Shah:** Writing – review & editing, Writing – original draft, Supervision, Data curation, Conceptualization. **Nazri Nayan:** Writing – review & editing, Conceptualization. **Ahmad Ibrahim:** Writing – review & editing,

Conceptualization. **Gholamreza Abdi:** Writing – review & editing, Validation. **Rana Muhammad Aadil:** Writing – review & editing.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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