Insect Meal a Nutritional Powerhouse for Aquafeed

Javeria Arif[1], Abdul Mateen[1,*], Andleeb Zahra[1], Mutaiyyba Akhtar[1], Asma Sajid[1], Ghazanfa Tariq[1], Laraib Ghulam Abbas[1], Noor Fatima[1], Shumaila Rani[1] and Alina Zulfiqar[1]

[1]Department of Zoology, Wildlife and Fisheries, University of Agriculture, Faisalabad, Pakistan
*Corresponding author: mateen117@yahoo.com

Abstract

The aquaculture sector significantly depends on fish meal and fish oil sourced from wild fish stocks. With concerns regarding overfishing and constrained marine resources, identifying alternate and sustainable feed sources is imperative. There are so many alternative sources that are easily available from animal and plant origin. Plant-based protein sources are abundant in proteins and have a balanced amino acid profile. However, its anti-nutritional factors may affect digestion in some species. Due to this drawback, animal-based alternative feed sources must be explored to replace fish meal, fish oil, and plant-based protein in aquafeed without adversely affecting productivity. For this reason, this chapter highlights the insect meal as a sustainable source of protein for aquaculture feeds. They possess a high protein content, and advantageous amino acid profiles, and can be generated from organic waste. Insects typically comprise 40 to 60 % protein and could substitute fish meal or plant-based ingredients. Insects necessitate minimal space and consume less energy for cultivation. Insect meal can be combined with other feed ingredients to create a balanced combination, which can then be extruded into pellets for better and more convenient feeding to cultured species.

Keywords: Aquaculture, Nutrition, Fish meal, Insect meals, Insect species, Aquafeed

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Introduction

Aquaculture is a practical solution to meet the food demands of the growing global population (Jannathulla et al., 2022). As a result, research activities in aquaculture have grown significantly in recent decades. Aqua-nutrition research has markedly progressed the current aqua-feed industry, which accounts for over 60% of aquaculture expenses, establishing aqua-feed as the essential component of the aquaculture sector (Xiong & Xu, 2024). For human consumption, it is acknowledged as a source of high-quality proteins (Stankus et al., 2021). The only way aquaculture can maximize its benefits to utilizing resources and integrating thoroughly into the global food chain (Verdegem et al., 2023). The major purpose of aqua-nutrition research is to examine the optimal nutrient requirements in aquaculture species. Aquaculture's heavy reliance on fish meal puts significant pressure on wild fish stocks, causing them to rapidly diminish (Stankus et al., 2021). Several research has been undertaken to identify the appropriate quantities of crude protein, amino acids, crude lipids, fatty acids, and vitamins in several commercially valuable aquatic species (Xiong & Xu, 2024). Researchers, policymakers and industry stakeholders frequently collaborate to identify solutions that strike a balance between the necessity of producing protein, protecting the environment and managing resources sustainably (Vala et al., 2024).

Protein Sources in Aquaculture

Fish meal is a traditional and widely used protein source in aquafeed. It is obtained from processed fish and is valued for its excellent protein quality, amino acid composition, and digestibility (De Marco et al., 2015). The use of byproducts from aquaculture in aquafeed has risen, although it will be inadequate to meet the anticipated aquafeed requirements by 2050 (Froehlich et al., 2018). The growing aquaculture industry will encounter a significant challenge due to the restricted availability of fish meal and fish oil, demanding the substitution of these ingredients in aquafeed (Quang et al., 2022). Over the past two decades, initiatives aimed at decreasing the proportions of fish meal and fish oil in aquafeed have resulted in a larger incorporation of plant-derived ingredients (Fry et al., 2016). Incorporating these ingredients into aquafeed, about environmental considerations, exerts pressure on land and water resources and produces waste in comparison to fish meal-based diets (Kokou & Fountoulaki, 2018). Numerous alternative ingredients for aquafeed have been examined, notably, insect meal and fishery by-products having the most significant capability to fulfill the protein demands for aquafeed in the future (Hua et al., 2019).

Major Challenges in Aquafeed

Several major challenges faced by fish farmers in the feed sector are restricted access to financing, insufficient technical advancements, inadequate understanding of feed formulation and processing, and substandard feed management and storage practices. In industries marked by rapid innovation and significant productivity increases, considerable fluctuations in output and input utilization may arise, resulting in higher costs (Vala et al., 2024). Livestock production, which occupies 70% of agricultural land, exerts significant pressure on limited resources. This, combined with the global increase in population as shown in (Figure 1) requires serious attention due to its influence on climate change and concerns about feed scarcity. These challenges impose constraints on investment prospects for a profitable and sustainable fish feed processing and manufacturing sector to satisfy the rising demand for fish meal (Munguti et al., 2021).

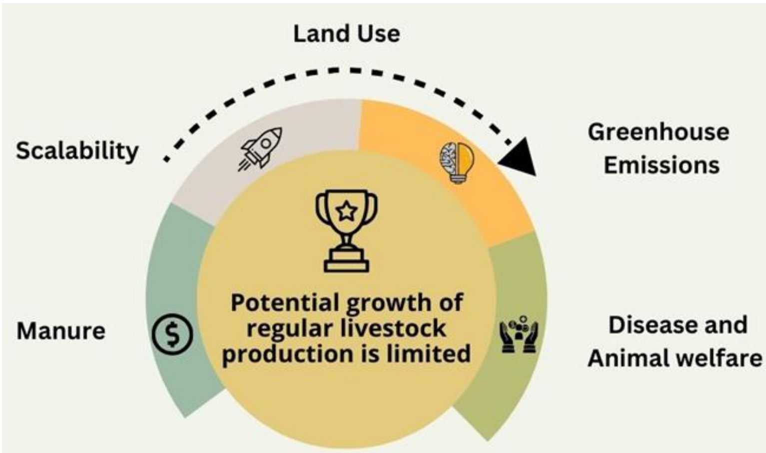

Fig. 1: Potential growth of regular livestock production is limited therefore, sustainable aquaculture growth depending on insect feed ingredients.

Another primary challenge in aquaculture is the heavy reliance on fish meal in commercial fish feeds. The origin of fish meal prompts sustainability owing to its effects on marine habitats. Overfishing of small pelagic fish for fish meal can disrupt the food chain and lead to cascading effects on other marine species (Tohivo et al., 2020). This entails identifying optimal ingredient combinations that supply essential nutrients for fish growth while reducing environmental effects. Developing and using alternative feed sources can sometimes be more expensive. The aquaculture business constantly faces the problem of striking a balance between the requirement for economically viable feeds and environmental methods. Meeting the nutritional needs of farmed fish is essential for their health and growth (Stankus, 2021). Confronting the challenges related to aquaculture feed demands a multidisciplinary strategy that encompasses research into alternative ingredients (more than 70% production cost) (Figure 2), advancements in feed technology and the implementation of sustainable practices to minimize environmental impact. The future of the aquaculture sector depends on sustainable methods, such as responsible feed management (Vala et al., 2024).

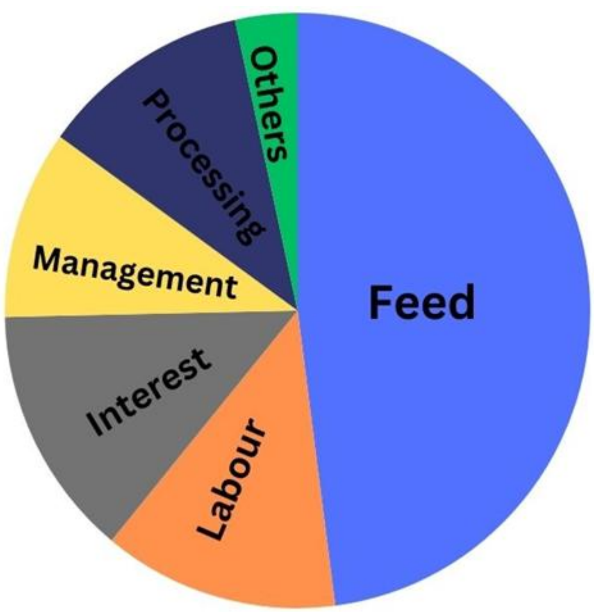

Fig. 2: Aquaculture production cost.

Need for Alternative Protein Sources

Rising costs and possible diminishing supplies of fish meal have prompted researchers to seek more economical and appropriate alternative protein sources for fish feed, primarily derived from animal or plant proteins (Van et al., 2015). More environmentally friendly solutions for feed production are provided by substitute protein sources such as plant-based proteins, insect meal, and single-cell proteins (Chakraborty et al., 2019). The economic viability of aquaculture operations may be enhanced by alternative protein sources, especially those obtained from plants and insect farming, which may provide more affordable and easily accessible options for feed production. Plant protein sources are widely accessible and typically command a lower market price than fish meal. Their incorporation in aquafeed is limited due to anti-nutritional aspects, despite their high protein content. Microbial proteins, both as isolates and whole-cell biomass, are regarded as novel protein sources; nonetheless, their higher nucleic acid content and toxicological aspects require more investigation across many aquatic species (Jannathulla et al., 2022).

Research on other feed sources is necessary to replace fish meal, fish oil, and plant-based protein in aquafeed without compromising output. Insect meal is becoming known as a sustainable and nutritious source for aquaculture diets. Insects are known for their efficient conversion of organic matter into protein making them a resource-efficient option for aquaculture feeds. This efficiency can positively impact the overall sustainability of aquaculture operations (Vala et al., 2024). Utilizing a varied assortment of feed components aids in providing a balanced and nutritionally comprehensive diet for aquaculture fish. Aquaculture, comparable to other agricultural practices, has environmental consequences, such as water pollution and habitat damage. Sustainable sourcing of alternative protein ingredients can help mitigate these environmental impacts contributing to more eco-friendly aquaculture practices. The growing aquaculture relies heavily on the availability of fish meal, the primary protein source in aquatic animal nutrition. The restricted supply and rising cost of fish meal have prompted the exploration or creation of other protein sources. However, the use of those proteins has been restricted by the associated problems, such as pro-inflammatory agents, anti-nutrients, and imbalanced amino acid profiles of alternative protein sources. Some concerted efforts were conducted to find alternative protein sources in insects (Vala et al., 2024).

Feasibility of Insect Meal in Aquaculture

Insect meal draws attention as an alternative to fish meal in aquatic and terrestrial animal diets due to its efficient conversion of organic matter into protein, the viability of commercial-scale production, and consumer acceptance making them a resource-efficient option for aquaculture feeds (Quang et al., 2022). This efficiency can enhance the overall sustainability of aquaculture operations. Relying on a varied selection of feed ingredients helps to create a balanced and nutritionally complete diet for farmed fish (Vala et al., 2024). Effective inclusion of insect meal in the predilection to fish meal in feed has been well-reviewed for many aquatic species. Insect meals exhibit beneficial characteristics, including a desirable nutritional composition, primarily categorized by high protein content and balanced amino acid profiles (Nogales et al., 2019). Enhancement of health in fed organisms and ecological advantages of insect-based diets linked to economic fish, land utilization, and solid phosphorus waste in contrast to insect-free diets (Gasco, 2021). The use of these insects for aquatic animals has gained increasing interest from research throughout the last few years (Tran et al., 2022).

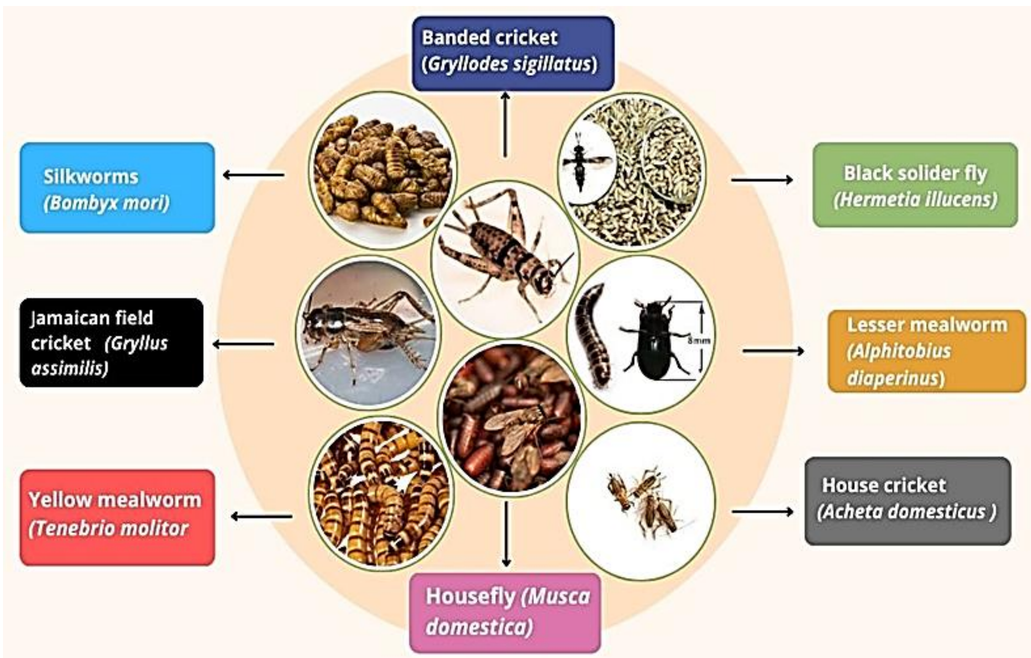

Fig. 3: Important insect species used in producing meals to replace fish meal in aquafeed.

Various Insect Species Used in Aquafeed

Insects are the most diversified group of animals and provide a natural food source for fish, particularly for carnivorous and omnivorous fish, as these fish species require relatively high amounts of proteins in their diets (Nogales et al., 2019). Among the species tested and used for industrial aquafeed production, eight species (Figure 3), including Black Soldier Fly (*Hermetia illucens*) Silkworms (*Bombyx mori*), Yellow Mealworm (*Tenebrio molitor*), Housefly (*Musca domestica*), House Cricket (*Acheta domesticus*), Jamaican Field Cricket (*Gryllus assimilis*) and Banded Cricket (*Gryllodes sigillatus*) is the most promising (Vala *et al*., 2024). These species are the most studied in replacing protein sources in aquafeeds. Legislation authorized the use of these species for aquaculture feed production (Daniel et al., 2018). The nutritional makeup of these insect species has been examined, including minerals, fatty acid profiles, crude protein, amino acid and fat. These insects appear to be conducive to large production and provide feed that can partially or completely substitute fish meal (Vala et al., 2024).

Due to their exceptional nutritional content, insects can provide a feasible and environmentally sustainable approach to the challenges of food production. Although cultural factors are detrimental to the rapid acceptance of entomophagy in more industrialized countries, the utilization of insects as components in animal feed is garnering significant interest and is currently undergoing study. The utilization of insects in the production of ingredients for the nourishment of animals is drawing considerable interest and is already being tested (Sanchez et al., 2014). Insects are thoroughly investigated as a component of the diets of both omnivorous and carnivorous species of freshwater and marine water fish, including those that inhabit brackish water and can endure varying salt levels (Nogales et al., 2019). Their primary nutritional composition is shown in Table 1 (Sanchez et al., 2014).

Feed from Insects: Specific Case Studies

Three distinct insect species stand out due to their breeding simplicity, widespread distribution, and exceptional efficacy in organic waste conversion. The Black Soldier Fly, the Yellow Mealworm and the Common Housefly are harmless to humans and the environment, demonstrating considerable potential for future production within the circular economy framework (Sanchez et al., 2014).

i.Black Soldier Fly

Black Soldier Fly (BSF) is extensively dispersed globally in temperate and tropical regions. Because BSF can convert low-value residual organic streams into products of high-value proteins, it is not a disease vector for people, animals, or plants (Tomberlin et al., 2020). A well-balanced profile of essential amino acids is exhibited by BSF. This profile is equivalent to that of *Musca domestica* and *Tenebrio molitor*, and in certain instances, it is superior to that of fish meal. The substrate utilized throughout the raising phase has a significant impact on nutritional values (Spranghers et al., 2016). Black Soldier Fly larvae contain high concentrations of minerals such as iron, manganese, copper, zinc, phosphorus and calcium (Barragan et al., 2017).

Table 1: The nutrient composition of fish meal, commercial meal and various insect meals.

Parameters	Units	Fish meal	BSFL	House fly	Super worm	Mealworm
Crude Protein	% DW	75	42	50	47	53
Dry Weight	%	25	44	25	42	39
Fat	% DW	10	35	12	42	39
Ash	% DW	14	21	10	2.4	3
Gross Energy	MJ/kg DW	22	22	23	25	27
Sodium	g/kg DW	11	1.3	5	1.1	0.9
Potassium	g/kg DW	12	7	6	8	9
Magnesium	g/kg DW	3	4	3.4	1.2	2.3
Calcium	g/kg DW	26	76	5	25	23
Zinc	g/kg DW	99	108	119	83	144

Numerous studies indicate that Black Soldier Fly (BSF) pre-pupae can partially or entirely replace fish meal in the diets of many fish species (Tran et al., 2015). Specifically, 15% and 30% of BSF meals were utilized to replace 25% and 50% of fish meals, as well as 35% and 74% of fish oil, respectively. No notable changes in growth performance were observed for BSF meal at the minimal replacement rates. At high levels, chitin present in pre-pupae may decrease digestion, hence reducing food availability for fish (Vala et al., 2024). The nutritional value of BSF larvae meal has been comprehensively studied: however, the impact that it has on the health of fish and gut health in particular has been less considered so far. However, a recent study indicates that the complete replacement of fish meal with BSF larvae meal does not adversely affect the intestinal health of Atlantic salmon. Conversely, the incorporation of insect meal into the diet appears to diminish excessive lipid accumulation within enterocytes in the proximal gut (li et al*.,* 2022)

ii.Common Housefly

The most common species at the global level is Common Housefly (*Musca domestica*). Common Housefly larvae can be nurtured on several substrates, showing the capacity to convert that waste that is organic, into useful biomass. Housefly larvae have proteins and lipids comprising 40% to 60% and 9% to 26% of dry matter, respectively. The protein content in Housefly pupae can increase by around 70% (Vala et al., 2024). The amino acid composition closely resembles that of a fish meal. The amounts of phosphorus, potassium, sodium, magnesium, and iron are comparable to those of the housefly, although calcium and magnesium levels become reduced by a factor of 15 and 3, respectively. The meal of Housefly (*Musca domestica*) is abundant in B complex vitamins, trace minerals, and phosphorus. Previous research indicates that Housefly meal can effectively substitute fish meal either partially or entirely in fish diets. The results indicated that no physiological stress was induced in the fish by consumption of Housefly meal (Saleh et al., 2020).

A 50% substitution of fish meal with Housefly larvae meal enhances the growth of Nile Tilapia (Wang et al*.,* 2017). Diets with 30%, 50%, and total fish meal replacement were employed, and numerous characteristics were assessed, revealing no noteworthy differences in feed consumption and apparent digestibility coefficients among the treatments. Moreover, substituting up to 75% of fish meal have no impact on growth performance or feed consumption. Nonetheless, total substitution of fish meal resulted in a markedly reduced survival rate, increase in weight, enhanced feed conservation ratio and specific growth rate (Cadinu et al*.,* 2020).

iii.Mealworm Beetle

The Mealworm Beetle is native to Europe but is now dispersed globally. The binomial nomenclature is *Tenebrio molitor*. It is a beetle that consumes grain, flour, and its derivatives. Its larvae are easily raised on low-nutritive plant and animal waste products (Terova et al*.,* 2019). They are commercially produced to be used as pet food (birds and reptiles) or fishing baits. Their composition includes proteins (47–60%) and lipids (31–43%), with amino acid and fatty acid profiles that are appropriate for incorporation into animal feeds. Use as a partial substitute for traditional protein sources such as Soybean meal or fish meal has been investigated in poultry and other aquatic species, including African Catfish, Nile Tilapia, Pearl Gentian Grouper, European Sea Bass, and Rainbow Trout (Biasato et al., 2017).

Favorable feedback has also been reported regarding the utilization of substantial Mealworm beetle contents. Mealworms, due to their high palatability, can substitute up to 45 percent of the fish meal in practical diets for African Catfish without significantly compromising growth performance and feed efficiency ratio (Wang et al., 2017). Mealworm has been effectively utilized in Rainbow Trout, capable of substituting up to 50% of dietary components. Notable outcomes have been achieved, particularly for marine carnivorous species such as European Sea Bass and Seabream where fish growth remained mostly unaffected with fish meal substitutes of 25 percent. European Sea Bass can be nourished for 42 days with 25% Mealworm larval feed, resulting in notable anti-bacterial activities and enhanced anti-parasitic action (Van et al., 2015). The incorporation of a full-fat diet of Mealworm larvae does not adversely affect the majority of quality traits in Rainbow Trout flesh, except the fatty acid profile (Gasco et al., 2018).

Physiological Responses of Fish using Insects as Protein Source

The formulation of the diet is crucial for the sustainable production of fish, as the diet's composition and nutritional value directly affect fish development performance and health status. Insects are widely recognized to possess bioactive compounds like chitin, at certain quantities, can enhance immunity in fish and facilitate the divergence of their gut microbiota (Terova et al., 2019). Recently, researchers have started developing novel aquafeed formulations, including insect meal, and investigating their impact on the physiological responses of various fish species. The inflammatory response in Rainbow Trout can be mitigated by incorporating BSF meal in low-FM diets (Bruni et al., 2020). Moreover, it observed that HI-based meal beneficially influences the intestinal physiology of different fish species. The replacement of 50% BSF meal for fish meal did not adversely affect the physiological responses of Zebrafish (Vala et al., 2024).

The incorporation of high levels of BSF meal adversely affected response to stress, oocyte maturation, spawning, and hatching in zebrafish (Hameed et al., 2022). No major change in growth performance was seen when fish meal was substituted with 20%, 40%, and 60% diets related to the control group (Tacon, 2020). The incorporation of complete BSF larvae meal in catfish diets resulted in reduced development and feed efficiency (Hameed et al., 2022). The incorporation of 50% BSF in the sturgeon's diet adversely impacted gut histological morphometric measures (Olivotto, 2022). The inclusion of a substantial quantity of BSF meal led to a decrease in gut microbial biodiversity, high lipids level, and marked activation of genes associated with immune response (Hameed et al., 2022).

Challenges to Adopting Insect Meal in Aquaculture

The utilization of insects has encountered challenges including safety concerns, inadequate lipid absorption, and limited protein bioavailability attributed to high levels of chitin (Vala et al., 2016). Research has underscored the potential of insect protein as a functional diet due to its immune-stimulant properties associated with the presence of chitin (Tohivo et al., 2020). The exoskeleton of insects is composed of the carbohydrate chitin. Chitin, a non-protein nitrogenous substance in most insect cuticles, leads to diminished meal digestibility and compromised developmental efficiency. Chitin in insects is predominantly indigestible to most fish, even with the presence of the chitinase enzyme. Alkaline extraction can efficiently remove chitin; nevertheless, it is expensive and produces pollutants and toxins (Caligiani et al., 2018).

The replacement of fish meal with Black Soldier Fly meal can diminish the concentration of some potentially toxic components, such as nickel, arsenic, and lead, in fish feed, thereby ensuring that harmful chemical levels in animal feed remain within permissible limits. It is now commonly recognized that dietary metal consumption can induce chronic toxicity in aquatic organisms. These contaminants can bio-accumulate within food chains (Vala et al., 2024). Consumption of PTE contaminates seafood, posing a significant threat to human health. Bioaccumulation of pesticides via insects in fish has also been reported. The low concentration of polyunsaturated fatty acids in terrestrial insects decreases their suitability as feed for marine fish (Bandara et al., 2018).

Regulations and standards related to the use of insect protein in animal feed can vary significantly between countries. The control of insect feed is a significant concern for the insect-rearing sector. In certain states of the United States, the use of insect-based feed is acceptable whereas other states await approval. There is an absence of adequate rules, laws, and legislation about insect cultivation and consumption (Usman et al., 2021). Therefore, future studies should concentrate on technological advancement to optimize insect production and elucidate the impact of insect meal on fish health (Bandara et al., 2018).

Possible Solutions to Challenges in Introducing Insects into Aquafeed

Chitin, that adversely affects fish growth, can be eliminated with the supplementation of chitinase or chitinolytic bacteria. This method is highly advantageous in stimulating immunological activity in fish and reducing the ecological effects of fish waste (Hameed et al., 2022). Proper growing of insect production can mitigate environmental effects, enabling insects to compete with traditional ingredients (Smetana et al., 2019). The environmental effect types of *T. Molitor*, *M. domestica*, and *H. illucens* significantly take to the feed produced by the insect-rearing sector. Consequently, supplying an appropriate substrate for insect cultivation and enhancing facility efficiency will significantly contribute to realizing the environmental advantages of insect meal (Thevenot et al., 2018).

Defatting is an alternative approach to enhancing amino acid content; nonetheless, it necessitates substantial energy consumption, hence high environmental effects and feed expenses. It is advisable to incorporate additional raw materials into insect meals that lack essential amino acids. Extrusion is a crucial manufacturing technique for optimizing nutrient use (Turchini et al., 2019). Recent studies also additionally demonstrate the efficiency of extruded insect-based feed. Environmental consequences can be moderated by the efficient management of feeding strategies to minimize feed waste and improve the feed conversion ratio. Innovative processing methods are required to reduce the safety risks associated with insect feed consumption (Weththasinghe et al., 2021).

Sustainable Development Goals

Conversely, one-third of food is wasted, while 8.9% of the global population is anticipated to be undernourished, and 26% experienced moderate to severe food insecurity in 2019. Insects minimize the above-mentioned socioeconomic challenges, offer healthier and more sustainable food, and decrease the production and consumption of animal feed. Implementing new and sustainable food production systems, such as insect farming, may advance numerous interconnected sustainable development goals (SDGs) (FAO *et al.,* 2020). Insect farming may directly or indirectly support multiple sustainable development goals (SDGs) (Mancini *et al.,* 2019). The objective of a sustainable consumption and production system is to convert energy and materials to improve human well-being while minimizing negative impacts on environmental resources. The interaction (Figure 4), while not exhaustive, can assist in developing effective policy in the insect industry within the framework of the SDGs and their corresponding targets (Moruzzo et al., 2021).

Fig. 4: Sustainable Development Goals.

Future Perspective

Ongoing research to optimize insect farming techniques, enhance nutrient profiles, and improve feed-to-insect biomass conversion efficiency is crucial for the future viability of insect meal in aquaculture. Designing space-efficient insect-rearing production facilities is essential for optimizing land use, with considerations that are specific to each species. Renewable energy sources have been proposed as a viable solution, with the potential to decrease the burden by around 25%. Subsequent life cycle assessment studies should concentrate on comprehensive perspectives about production facilities and their locations, in conjunction with appropriate substrates for insect rearing. The bioconversion method for insect cultivation represents a sustainable approach to food security. Consequently, the approach generates no waste and reduces the reliance on expensive protein sources like soy meal and fish meal in aquafeed (Hameed et al., 2022). Recent research has shown that different parts of insects, including meal, oil, pulp, and paste, can be utilized in aquaculture. However, there is limited information available about the use of pulp and paste, thus there is a need for further research (Gangopadhyay et al., 2022). A sustainable consumption and production system aims to transform energy and materials for human well-being while minimizing negative impacts on environmental resources. Innovations in insect farming technology, encompassing automation and precision agriculture techniques, can enhance efficiency, lower production expenses, and facilitate scalability (Rawski et al., 2020).

Conclusion

This chapter aims that insects possess significant potential to replace fish meal because of their nutritional content. It has been studied that employing insect meal as an alternative source of protein, could enhance the aqua food systems' social and economic performance while also benefiting the environment. Insect meals have a substantial food profile, particularly in protein, along with significant levels of minerals and vitamins, presenting notable economic and environmental benefits. Specific constituents in insect meals serve as functional nutrients that augment the immunological condition of animals. Furthermore, the antimicrobial qualities of insect feeds provide a natural substitute for pharmaceutical medicines and antibiotics utilized in aquaculture. Appropriate processing technologies can enhance the nutritional quality of insects. The favorable physiological effects of insect-based diets in numerous fish species make insect meal a viable protein source for various aquatic species' diets. Our study emphasized the difficulties associated with utilizing insects in aquafeed, as well as potential solutions to these issues. However, additional research is necessary to ascertain the requisite levels for aquatic organisms, which differ by species and developmental stages.

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