AQUACULTURE FEED

MAGAZINE AFRICA

VOLUME 1 - ISSUE 4 - 2024

INSECTS AN ALTERNATIVE FOR SUSTAINABLE SUSTAINABILITY OF AQUACULTURE FEEDS IN AFRICA

ALTERNATIVE PROTEIN SOURCES IN AQUAFEED: CURRENT SCENARIO AND FUTURE PERSPECTIVES

EXPLORING SUSTAINABLE ALTERNATIVES IN AQUACULTURE FEEDING: THE ROLE OF INSECTS

RECENT ADVANCES IN THE UTILIZATION OF INSECTS AS AN INGREDIENT IN AQUAFEEDS

AQUACULTURE FEED

MAGAZINE AFRICA

The African Aquaculture Feed Magazine is an essential tool for the development of aquaculture feed management in the region. Indeed, the magazine offers a valuable and up-to-date source of information on the latest advances in aquaculture feed, new market trends, best management practices and technical recommendations for improving aquaculture production.

By providing feature articles, case studies, market analyses and interviews with industry experts, Africa's aquaculture feed magazine enables aquaculture professionals to stay informed and up to date with the latest innovations in fish and shellfish feed. This enables them to adapt their practices in a more sustainable and efficient way, taking into account the environmental, economic and social issues linked to aquaculture production.

In addition, the Africa Aquaculture Feed Magazine also helps to promote good feeding practices in aquaculture, highlighting innovative initiatives and projects that are having a positive impact on the sustainability of aquaculture production in the region. By fostering the sharing of knowledge and experience between industry players, the magazine plays an essential role in building the capacity of aquaculture professionals and in the continuous improvement of aquaculture feed management practices in Africa.

The Africa Aquaculture Feed Magazine is a contributing tool for the development of aquaculture feed management in the region, informing, raising awareness and inspiring industry players to adopt more sustainable practices and contribute to the growth and prosperity of aquaculture in Africa.

LIST OF THE EDITORIAL TEAM OF THE AFRICA AQUACULTURE FOOD MAGAZINE

Dr Arnold Ebuka Irabor. Sustainable Aquaculture, Fish Nutrition Department of Fisheries, Dennis Osadebay University, Asaba, Nigeria

Dr Abd El Rahman Khattaby. Senior research at central laboratory of aquaculture Agriculture Research Center,.Egypt.

Dr Mohamed Abo Elsoud. Expert in Aquaculture feed quality Egypt.

Dr Mostafa A. M. Soliman. Utilization of by-Products Department, Animal Production Research Institute (APRI). Agriculrture Research Center, ElDokki, Giza, Egypt

Dr Mustapha ABA. Aquaculture Expert. Fish Nutrition. Rabat Morocco.

Dr Nesara K.M Fish nutritionist, Quality and Nutritional of fish feed expertise Inde.

Dr Prasanta Jana. Fish Nutrition, Biochemistry & Physiology Division, ICAR-Central Institute of Fisheries Education, Versova, Mumbai 400061, Maharashtra, India.

Dr Samwel Limbu. Aquaculture nutrition and Environmental Health. Lecturer at University of Dar es Salaam. Tanzania.

Dr - Vaitheeswaran Thiruvengadam. Fisheries and Aquaculture Department. International University of East Africa, Kampala, Republic of Uganda.

Paul Mosnier. STEM graduate with a specialisation in aquaculture. Strong understanding of the aquaculture industry and the scientific publishing landscape. Journal Aquaculture. Frontiers.

Dr Rachid Ganga. Aquaculture Department. Hassan II Agronomic and Veterinary Institute. Agadir.

Dr Eman Abo Shady. Aquaculture Researcher /Biology-sustainable Aquaculture.
feed Technology. Cairo. Egypt

Dr. Osama A. Zenhom. Fish Nutrition. Central Aquaculture Research Laboratory, Agricultural Research Center, Abbasa. Egypt.

EDITORIAL

DEAR READERS

Due to the increasing demand for fish and fish products as an alternative source of animal protein caused by the steady growth of the human population in Africa, the aquaculture sector has undergone a remarkable expansion over the past decades in the continent. With the growth of the sector, the availability of feed of high nutritional quality, digestibility, palatability and minimal waste production are among the main obstacles to be faced for the productive sustainability of African aquaculture.
While fishmeal is expensive and unsustainable for aquaculture operators, vegetable proteins can have a negative impact on the nutritional quality of some farmed fish, so the search for quality protein alternatives that meet sustainable production standards has become an issue of great importance for the productive growth of aquaculture in Africa, where the price of fishmeal is a major impediment to the development of aquaculture, especially on a small scale.

Feed represents the largest economic expense in the aquaculture production sector, varying from 40 to 70% of the production cost due to the cost of available raw materials. Faced with this situation, the production sector is still under pressure to develop ways of promoting greater sustainability in the aquaculture production chain, especially with the depletion of fish resources due to overfishing, so there is an urgent need to explore a sustainable alternative diet that is both nutritious and environmentally friendly for sustainable commercial fish production. To achieve this, insects have been promoted as a beneficial source of protein for fish feed, as is whether this is a genuine alternative or rather a natural choice for modern birds or fish that have been on earth for over 60 million years, which in wild conditions do not have access to soya meal, fishmeal or other raw materials that have been developed over the last few decades of animal production and feeding.

Furthermore, there is clear evidence that the last decade has been the most intensive period for exploring the use of insects as meal in aquaculture feeds.

Their high nutritional value combined with their digestible quality make the use of insects a promising alternative for aquaculture feed in Africa, mainly because of their potential use to replace traditional ingredients used in nutritional formulations, such as soybean meal and fishmeal.

The various aspects that make the use of insects a viable feed alternative for aquaculture include palatability, good digestibility, an amino acid profile similar to that of fishmeal, ease of cultivation in captivity and the possibility of nutritional manipulation, depending on the species and stage of development (larva, nymph or adult).

The main objective of this issue of the Magazine Aliment d'Aquaculture Afrique is to explore, through these various research articles, the role of insects in as a sustainable alternative source to fish meal and the research carried out both in Africa and on other continents concerning the use of insects in the aquaculture feed sector.

Enjoy your reading.

SUMMARY

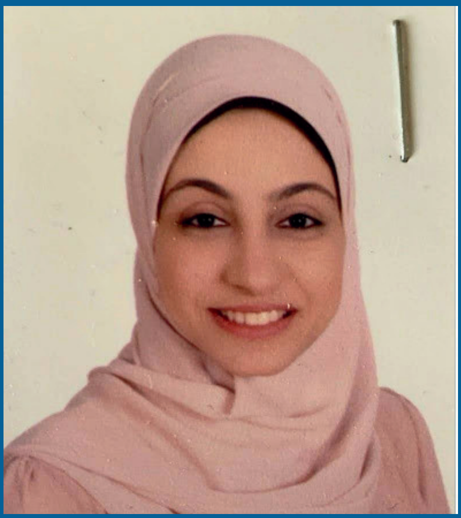
ARTICLES

ACTUALITÉS

ÉVÈNEMENTS

ARTICLES

EXPLORING BLACK SOLDIER FLY LARVAE AS A SUSTAINABLE PROTEIN ALTERNATIVE IN AQUACULTURE FEED: IMPLICATIONS FOR FISH AND CRUSTACEAN NUTRITION IN AFRICA



Dr Eman Abo Shady. Aquaculture Researcher /Biology-sustainable Aquaculture. feed Technology. Cairo. Egypt

The African aquaculture industry faces the challenges of meeting the nutritional requirements of fish and crustaceans while reducing environmental impacts and controlling costs. Black soldier fly (BSF) larvae (Hermetia illucens) have emerged as a viable alternative to traditional fishmeal, offering sustainability, economic viability, and robust nutritional profiles. This review compiles recent research focusing on the potential benefits of BSF larvae in aquaculture feeds in Africa, examining species-specific impacts on growth, health, and feed efficiency.

Findings show BSF larvae not only support growth and development in aquaculture species but also provide significant environmental and economic benefits, positioning them as a solution to sustainably scale aquaculture across Africa.

1. INTRODUCTION

African aquaculture holds immense potential to address food security and economic development goals across the continent. However, a central challenge is the high cost and environmental impact of traditional fishmeal-based aquafeeds. Over-reliance on fishmeal—derived from wild fish—places pressure on marine ecosystems, leading to concerns about resource depletion and environmental degradation. The high costs and supply volatility of fishmeal further limit its accessibility, particularly for small-scale fish farmers in Africa. To meet these demands sustainably, alternative protein sources are crucial.

Black soldier fly (BSF) larvae, with their high-quality protein and lipid content, have emerged as a promising alternative to fishmeal. BSF larvae can be farmed on organic waste, contributing to waste recycling and providing an economically viable protein source for aquaculture feeds. This review examines recent studies on BSF larvae as an aquafeed ingredient, with a specific focus on its applications in African aquaculture. It highlights the nutritional benefits, environmental impacts, economic feasibility, and specific case studies that underscore the growing potential of BSF larvae in Africa's aquaculture landscape.

2. NUTRITIONAL COMPOSITION AND BENEFITS OF BLACK SOLDIER FLY LARVAE

BSF larvae contain high levels of essential amino acids, lipids, and micronutrients critical for the growth and health of aquaculture species. The larvae's amino acid profile is comparable to that of fishmeal, meeting the requirements of fish and crustaceans for rapid growth and immune resilience.

Furthermore, BSF larvae are highly digestible, with protein and lipid content varying according to the larvae's diet, thus allowing for targeted nutritional formulations.

3. NUTRITIONAL COMPOSITION OF BLACK SOLDIER FLY LARVAE VS. FISHMEAL

Nutrient	Black Soldier Fly Larvae (%)	Fishmeal (%)
Protein	35-50	60-65
Lipids	20-30	10-12
Lysine	3.5-4.2	5.5
Methionine	0.9-1.2	1.2
Calcium	5.0	5.5
Phosphorus	1.5	2.0

Source: Based on the general nutrient ranges provided by studies such as Giarratana et al. (2021) and Fawole et al. (2020).

3.1 PROTEIN AND AMINO ACID PROFILE

Studies have shown that BSF larvae's protein composition contains essential amino acids, such as lysine, methionine, and tryptophan, which are necessary for growth and health in aquaculture species.

The protein content ranges between 35% and 50%, depending on rearing conditions, making BSF larvae a suitable substitute for fishmeal in high-protein diets.

The lipid content also provides essential fatty acids, such as lauric acid, which offers antimicrobial benefits.

3.2 MINERAL AND VITAMIN COMPOSITION

In addition to macronutrients, BSF larvae contain micronutrients essential for fish and crustaceans. The larvae are rich in minerals such as calcium, phosphorus, and magnesium, supporting bone health and metabolic functions.

Additionally, the larvae's high chitin content has been shown to enhance immune responses in fish, further supporting its role in aquaculture nutrition.

4. CASE STUDIES AND REGIONAL APPLICATIONS OF BSF LARVAE IN AFRICAN AQUACULTURE

4.1 NUTRITIONAL ADEQUACY AND HEALTH BENEFITS IN FISH AND CRUSTACEANS

Giarratana et al. (2021) investigated BSF larvae as an alternative to fishmeal, focusing on its efficacy in supporting the growth and health of various aquaculture species. Conducted as a systematic review, the study concluded that BSF larvae provide comparable, if not superior, nutrient profiles to traditional fishmeal. The larvae meal was shown to promote favorable growth and immunity outcomes across species such as tilapia and catfish.

The environmental footprint of BSF larvae production is considerably lower than that of fishmeal, with reduced energy consumption and lower greenhouse gas emissions. This study underscores BSF larvae's potential to transform African aquaculture by meeting both nutritional and environmental requirements.

4.2 ENHANCED GROWTH OUTCOMES IN TILAPIA PRODUCTION

Teye-Gaga (2017) conducted research on the inclusion of BSF larvae meal in Nile tilapia (Oreochromis niloticus) diets in Ghana. The study observed that replacing 50-75% of fishmeal with BSF larvae meal enhanced feed conversion ratios, growth rates, and nutrient absorption efficiency in Nile tilapia fingerlings.

Additionally, BSF meal-fed tilapia showed stronger immune markers and lower susceptibility to common aquaculture pathogens. The economic analysis further demonstrated the cost-effectiveness of BSF larvae meal, reducing feed costs by 20-30%.

The findings indicate that BSF larvae meal could bolster tilapia farming in Sub-Saharan Africa, enhancing both profitability and sustainability.

Species	Diet Type	Weight Gain (%)	Feed Conversion Ratio (FCR)
Nile Tilapia	Fishmeal	100	1.5
	BSF Meal	98	1.4
African Catfish	Fishmeal	100	1.8
	BSF Meal	102	1.6

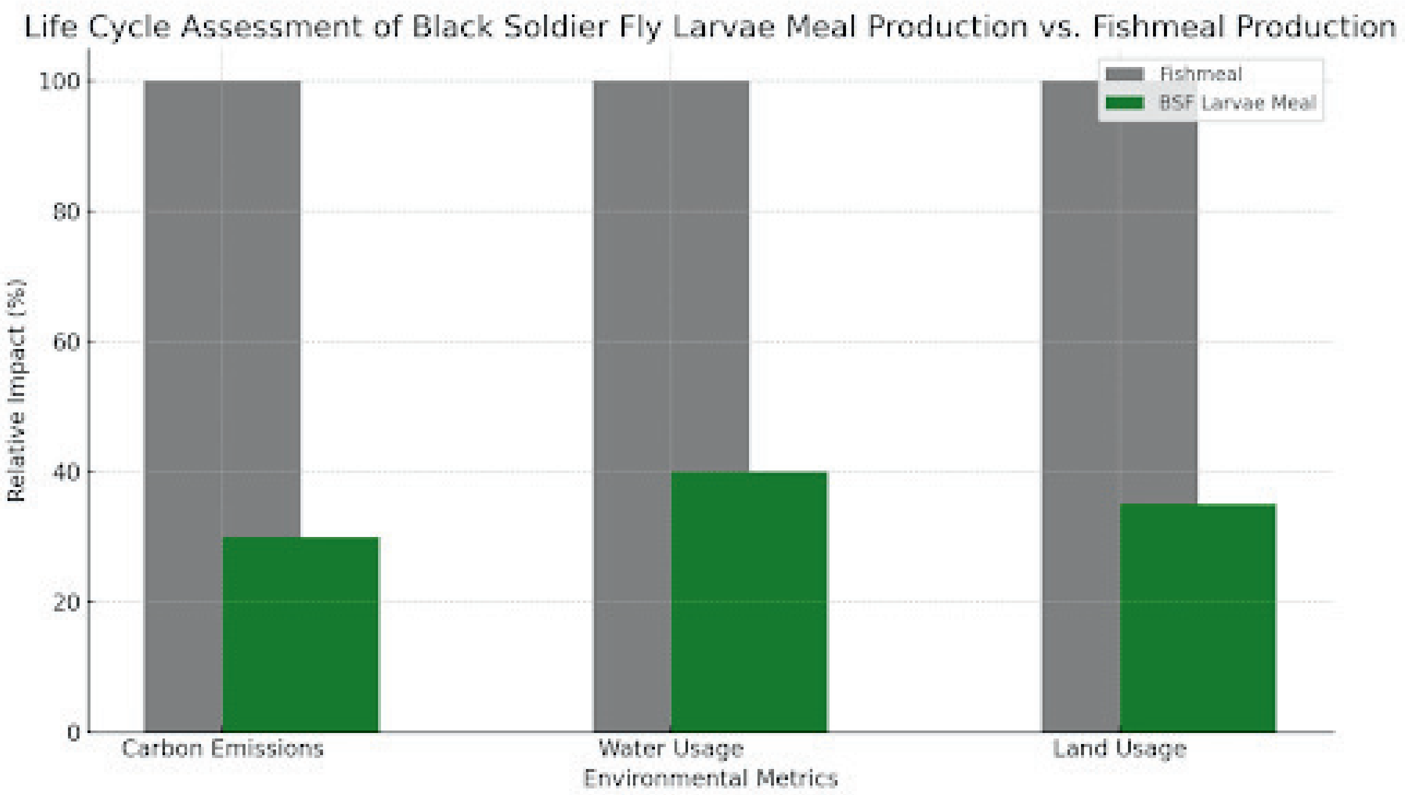
Source: Summarized from Teye-Gaga (2017) and Fawole et al. (2020) studies on growth and feed efficiency.

4.3 ENVIRONMENTAL SUSTAINABILITY ANALYSIS IN SOUTH AFRICAN AQUACULTURE

Using life-cycle assessment, Kleyn (2023) examined the environmental implications of replacing fishmeal with BSF larvae meal in South Africa.

This study demonstrated a 40% reduction in carbon emissions and water usage associated with BSF larvae meal production compared to fishmeal, alongside decreased reliance on marine resources.

The results suggest that widespread BSF adoption in aquaculture could align with South Africa's conservation policies and reduce environmental pressures.



- **Carbon Emissions:** BSF larvae meal production shows a substantial reduction (30%) compared to fishmeal.
- **Water Usage:** BSF larvae meal uses about 40% of the water required for fishmeal production.
- **Land Usage:** BSF larvae meal requires 35% of the land footprint needed for fishmeal.

4.4 GROWTH AND PHYSIOLOGICAL IMPACT IN AFRICAN CATFISH

In Nigeria, Fawole et al. (2020) explored the effects of BSF larvae meal on growth and health indicators in African catfish (Clarias gariepinus). BSF larvae meal demonstrated comparable growth performance and better nutrient utilization efficiency than traditional fishmeal.

Additionally, the study found that BSF larvae meal improved blood parameters, such as hematocrit levels and leukocyte counts, which are indicators of strong immune function.

These results highlight BSF larvae's potential in supporting resilient aquaculture practices in African catfish farming.

4.5 ECONOMIC VIABILITY FOR SMALL-SCALE FARMERS

Bartucz et al. (2023) assessed the financial feasibility of BSF larvae meal as a cost-effective alternative in the diets of rainbow trout and African catfish.

he study found that incorporating BSF larvae meal into feeds could improve profitability due to lower feed costs.

Analysis indicated that BSF meal could reduce feed costs by approximately 25% without negatively impacting growth or health, enhancing the viability of aquaculture for small-scale African farmers.

5. DISCUSSION

5.1 NUTRITIONAL EFFICACY AND SPECIES-SPECIFIC PERFORMANCE

The findings across studies highlight BSF larvae as a nutritionally adequate substitute for fishmeal.

BSF larvae meal was observed to support growth, immunity, and efficient nutrient absorption across various species.

In Nile tilapia, African catfish, and other regional species, BSF larvae offer protein content comparable to fishmeal, enabling better feed conversion and reduced reliance on additional nutritional supplements. Such performance is crucial in regions where protein feed sources are scarce and expensive.

5.2 ENVIRONMENTAL IMPACT AND SUSTAINABILITY

Life-cycle assessments indicate BSF larvae meal's positive impact on the environment. The reduced need for marine fish stock, combined with lower greenhouse gas emissions and decreased land and water use, underscores the sustainability of BSF larvae as an aquafeed.

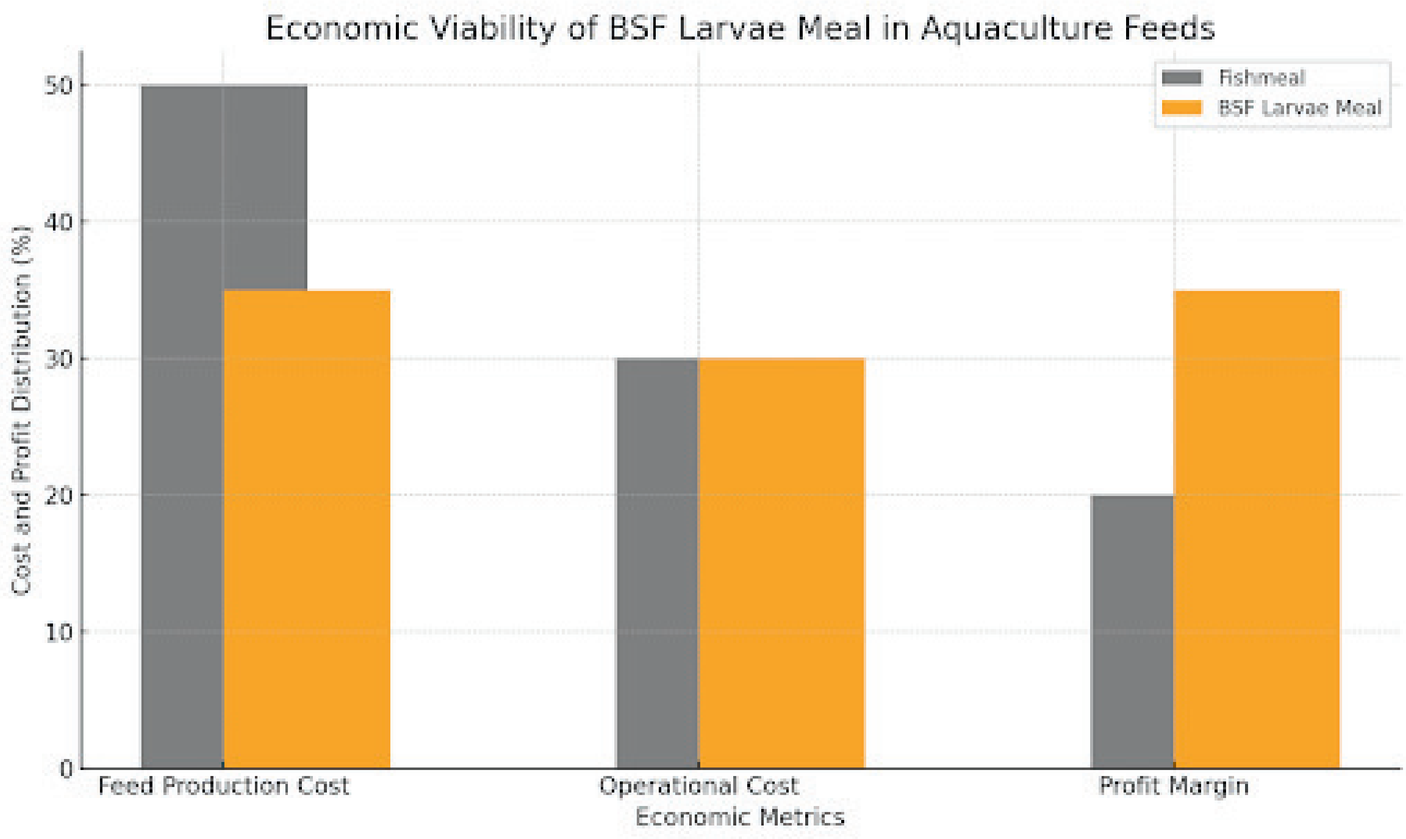
In South African contexts, as reported by Kleyn (2023), the shift towards BSF larvae could contribute to national conservation efforts by promoting circular economy principles and reducing ecological strain from traditional fishmeal.

5.3 ECONOMIC FEASIBILITY AND ACCESSIBILITY FOR AFRICAN FARMERS

From an economic perspective, the adoption of BSF larvae meal could lower feed production costs, increasing profitability for fish farmers.

By converting organic waste into high-protein feed, BSF larvae farms offer a locally available, cost-effective alternative.

Small-scale farmers, who often face challenges in accessing high-quality fishmeal, could benefit from this scalable protein source, fostering growth in local aquaculture industries.



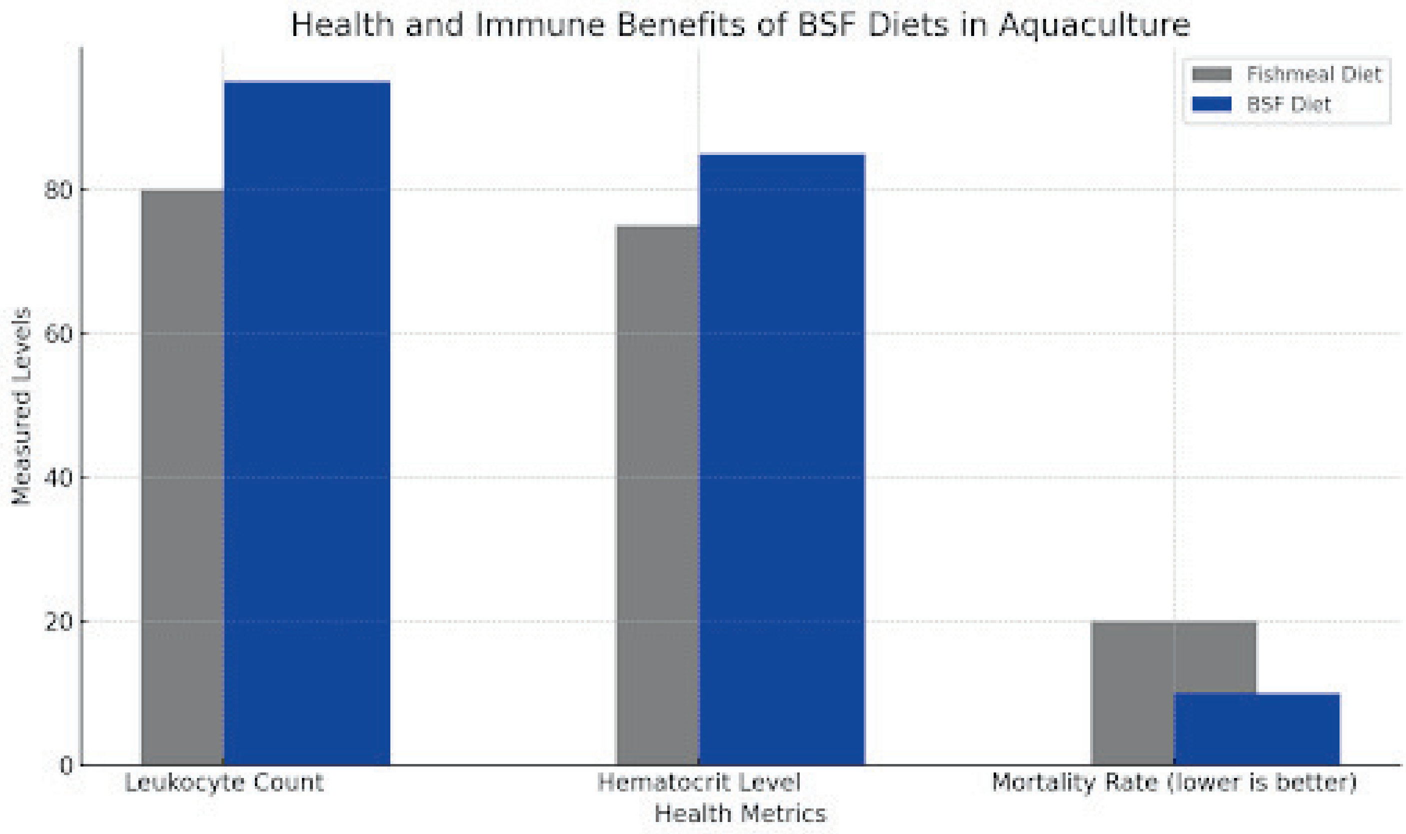
- **Feed Production Cost**: BSF larvae meal has a lower production cost (35%) compared to fishmeal (50%), showing potential cost savings.
- **Operational Cost:** Both feed types have similar operational costs.
- **Profit Margin:** BSF larvae meal allows for a higher profit margin (35%) than fishmeal (20%).

5.4 IMMUNE HEALTH AND DISEASE RESISTANCE

BSF larvae meal has been shown to enhance immune responses in aquaculture species, particularly through elevated leukocyte counts and improved hematological parameters.

This could reduce the need for antibiotics or other disease control measures, contributing to a more resilient aquaculture system.

For instance, Fawole et al. (2020) observed that African catfish fed on BSF larvae meal exhibited stronger immune function, a benefit that could enhance disease resilience and reduce mortality rates.



- **Leukocyte Count**: Higher in BSF-fed fish, indicating enhanced immune response.
- **Hematocrit Level**: Elevated in BSF diets, reflecting better health.
- **Mortality Rate**: Lower in BSF-fed fish, showcasing improved resilience.

6. LIMITATIONS AND CHALLENGES

The large-scale implementation of BSF larvae in aquaculture feed faces several challenges. Infrastructure for insect rearing, potential nutrient variability, and regulatory frameworks require further development across Africa.

Quality control and standardization of BSF larvae meal are necessary to ensure consistency in nutritional content and safety.

Moreover, public perception and regulatory acceptance of insect-based feeds remain barriers that must be addressed through awareness campaigns and industry support.

7. CONCLUSION

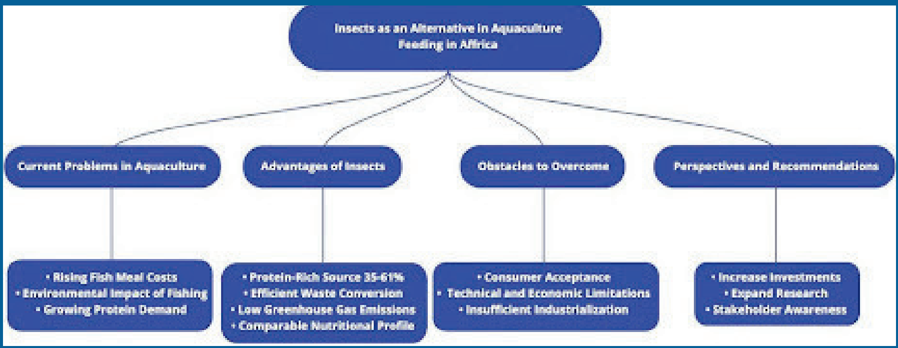
Black soldier fly larvae represent a promising and sustainable alternative to fishmeal in African aquaculture. The studies reviewed confirm BSF larvae meal's potential to enhance growth performance, economic viability, and environmental sustainability in aquaculture feeds. As Africa aims to scale its aquaculture industry to meet growing food demands, the adoption of BSF larvae meal could play a transformative role. Expanding BSF larvae production infrastructure, along with regulatory support and public awareness initiatives, is essential for unlocking the full potential of BSF larvae in Africa's aquaculture sector.

INSECTS AN ALTERNATIVE FOR SUSTAINABILITY OF AQUACULTURE FEEDS IN AFRICA

The growth of aquaculture and the increasing demand for farmed fish have led to an increase in the price of meal and used in fish feed in recent years, which represents a constraint for the development of aquaculture in Africa, considering that aquaculture feed represents 50 to 70% of production costs, this has led to a growing interest in alternative sources. Over the last decade, insect meal has gained popularity in the aquaculture feed industry in Africa, due to the rising costs and decreasing availability of fish meal, insect meal is now seen as a promising ingredient in aquaculture due to its nutritional value, efficient feed conversion and sustainable production potential.

The growing interest in insect meal as a substitute for fishmeal in aquaculture has gained momentum in recent years, following the significant number of scientific publications and research studies devoted to the subject, indicating a growing recognition of the potential benefits of insect meal.

By : Dr Mustapha ABA. Aquaculture Scientific Expert. Fish Nutrition. Rabat. Morocco.



INTRODUCTION

Due to the rapid growth of the human population and rising living standards, the demand for seafood is increasing (Alfiko et al., 2022). With the decreasing availability of wild fish and shellfish, the only way to meet the growing demand for animal protein is through aquaculture (Daniel, 2018 ; Stankus, 2021).

Africa's population is expected to reach around 2.53 billion by 2050 (UN, 2023) and the demand for food and protein will increase dramatically, which the current linear food system may not be able to meet.

Consequently, the aquaculture food production sector will play a key role in food and nutritional security on the continent, as aquaculture is the fastest growing food production sector and a major contributor to global fish production (FAO, 2024).

According to the latest statistical report published by the Food and Agriculture Organization of the United Nations (FAO, 2024), global aquatic animal production reached a new world record of 185 million tonnes (live weight equivalent), with a forecast of 204 million tonnes in 2030. Aquatic animal farming produced around 94 million tonnes, or 51% of the total, overtaking capture fisheries for the first time, which produced 91 million tonnes (49%) (FAO, 2024).

Aquaculture feed is a critical factor influencing the production of the aquaculture industry and affecting its output, since it accounts for 50-70% of production costs (Aba, 2020), which represents a constraint on the development of aquaculture in Africa.

Nutrition plays a key role in the aquaculture industry, influencing fish growth and health, as well as the quality of the end product, farm profitability and waste production.

The development of balanced, efficient and cost-effective diets that meet the nutritional requirements of species has made aquaculture nutrition one of the most important areas of research and development in the sector (NRC, 2011; Fiorella et al., 2021).

FISHMEAL IN AQUACULTURE NUTRITION

Fishmeal, generally obtained from marine fish, is commonly used as the main source of protein in aquaculture feeds due to its high nutritional value and its attractiveness to various aquatic species (Daniel, 2018; Dhar et al., 2024). Rich in nutrients, FM is the best source of high-quality protein with a balanced content of amino acids, omega-3 polyunsaturated fatty acids, minerals, vitamins (biotin, choline, vitamins A, D, E and B12) and trace elements (iodine and selenium) (Hardy, 2010; Macusi et al., 2023; Hussain et al., 2024). Fishmeal represents 50 to 70% of the total material in fish feed (Jannathulla et al., 2019). It is highly regarded as a source of dietary protein because it has an excellent amino acid composition and is easy to digest (Olsen et al., 2019). However, its use means that the farming of farmed fish depends on the capture of organisms from the natural environment, a situation that does not favour sustainable aquaculture and also makes this meal an expensive input due to the current fishing situation, all of which have caused the price of FM to increase by around 300% in recent years (Hussain et al., 2024).

Fishmeal (FM) is obviously insufficient to meet the huge demand for fish feed from growing aquaculture production, so there is an urgent need to find an alternative protein source to replace fishmeal (FAO, 2022; Wang et al., 2023). Among the sustainable solutions suggested for the aquaculture production sector is a shift from conventional to alternative food systems (FAO, 2020).

It is for this reason that aquaculture research aims to reduce the use of FP in feed by finding more sustainable and cost-effective substitutes, but with comparable protein quality. Consequently, the search for alternative and sustainable proteins has become a topic of great importance (Lin et al, 2022; Bansemer et al., 2023).

In Africa, the aquaculture sector has developed in response to the growing demand for fish protein resulting from population growth and changing dietary preferences (FAO, 2022). The continent's growing intensive aquaculture relies heavily on the availability of high-quality feed, traditionally based on fishmeal (FM).

However, the availability of FM is becoming increasingly limited, making it expensive and unaffordable (FAO, 2020) for most aquaculture producers in Africa.

PLANT MEALS

In the search for sustainable solutions, the scientific community has been faced with the challenge of finding alternative proteins to FM that reduce the pressure on fisheries and are more environmentally friendly (Torrecillas et al., 2017; Reis et al., 2019). When considering these alternatives, several factors need to be analysed to ensure their technical and economic feasibility, including protein content and nutritional quality (i.e. EAA profile and digestibility), the presence of anti-nutritional factors (ANFs) and production costs (Gatlin, 2007; Hardy, 2010; Oliva-Teles et al., 2015).

The main problems with these plants are their unbalanced essential amino acid (EAA) profile, in particular methionine and lysine deficiency, low protein content, high NFA and fibre content and non-digestible carbohydrates which affect their use as an alternative feed for fish (Glencross et al., 2014; Cummins et al., 2017; Simmon et al., 2021), in addition, plant-based feeds are less suitable for fish (Daniel, 2018, Alfiko et al., 2022), furthermore, plant proteins are highly vulnerable to mycotoxin contamination that could adversely affect fish growth and health (Maulu et al., 2024).

There is therefore an urgent need to explore other sustainable solutions.

INSECTS MEAL

Insects are the most abundant species on earth, both on land and in water. Within the arthropod phylum, insects are grouped as the most common type of segmented animal (Giribet and Edgecombe, 2019). The production of insects as a food source is seen as a viable strategy that could transform the current food framework of animal protein production sectors (FAO, 2013; Van Huis, 2019).

Currently, an increasing number of feeding trials have been conducted using insect meals to replace part of the FP in aquaculture species, and most of this research has shown promising results of replacing part or all of the FP with insect meals, although this depends on the fish and insect species. (LU et al., 2020 ; Hua, 2021 ; Liland et al., 2021).

INSECTS SOURCES OF PROTEINS

Unlike fishmeal and plant proteins, insects can be produced intensively in a short period of time with low arable land requirements, reduced water consumption/use, lower greenhouse gas (GHG) emissions and conversion to biowaste (Gasco et al., 2020 ; Pulido-Rodriguez et al., 2021).

In recent years, the use of insect meal in aquaculture has grown exponentially, due to its nutritional value, particularly as a source of protein (Belghit et al., 2019; Guerreiro et al., 2020; d'Alfiko et al., 2021); Kierończyk et al.,2022) and Karapanagiotidis et al., 2023).

Table 1 summarises the amino acid profiles of fishmeal, soybean meal, black soldier fly meal and milling beetle meal.

Table 1. Essential amino acid profile (% amino acid/100 g protein) in two insects and two meals (FM and SM) used in aquaculture.

	Arg	His	Ile	Leu	Lys	Met + Cys	Phe	Thr	Trp	Val
BSF	5,4	3,1	4,7	6,4	6,4	2,4	4,7	3,8	1,0	**8,6**
TM	5,6	**3,5**	**4,8**	**9,2**	6,0	2,6	4,0	3,9	0,9	6,4
FM	6,2	2,4	4,2	7,2	**7,5**	**3,5**	3,9	**4,1**	1,0	4,9
SM	**7,6**	3,1	4,2	7,6	6,2	2,7	**5,2**	3,8	**1,4**	4,5

BSF : Black Soldier Fly ; TM : Tenebrio molitor ; FM : Fishmeal ; SM : Soybean meal.

The amino acid profile presented by MSN and TM meals shows adequate levels of most of the essential amino acids, compared with fish meal. With regard to the amino acids present in the dry matter of the different insect meals (Table), black soldier fly in particular resembles the composition of fishmeal and may be one of its possible substitutes (Henry et al., 2018; Lu et al., 2020; d'Alfiko et al., 2021 and Kierończyk et al., 2022).

INSECTS SOURCES OF LIPIDS

Research into the effects of including insect products in fish feeds has mainly focused on insect meal as a source of protein rather than insect oil/lipids as a source of lipid (Hossain et al., 2023). The fat content of insects varies considerably, from 10 to 60%, and is generally lower in adults than in larvae or pupae (Xiaoming et al., 2010; Barroso et al., 2023).

Insects are also rich in n-6 fatty acids but deficient in n-3 fatty acids (Hawkey et al., 2021), so different strategies are used to improve the fatty acid profile of insects. The n-3 fatty acid content can be increased by using an appropriate substrate, thereby improving the nutritional value of insects (Hameed et al., 2022).

INSECTS IN ANIMAL FEED IN AFRICA

Entomophagy (the consumption of insects by humans) is a practice that has accompanied humans throughout their history and continues to be relevant in various regions of the world, mainly in Asia, South and Central America, as well as in Africa. In most countries on the continent, insects are mainly consumed as supplementary food (Paiko et al. 2012; van Huis et al. 2013; Niassy et al. 2016; Babarinde et al., 2021). Of all insect species, more than 2,000 edible species have been recorded worldwide, of which 470 species are found in Africa (Van Huis, 2013; Kelemu et al., 2015). Several studies have reported that the incorporation of insects into animal diets has been widely reported to have nutritional, economic, environmental and health benefits (Abro et al., 2020; Tanga et al., 2021; Chia et al., 2021; Kolobe et al., 2024).

Industrialisation of edible insect production, commercial processing and product development remains limited in some parts of the world, including Africa (Tanga and Kababu, 2023). Several food manufacturers in Africa have shown significant motivation and willingness to pay for and integrate insect-derived proteins into animal feed (Chia et al., 2020) and it is established that around 2,300 active insect farms exist on the continent (Figure 4), of which less than 2% are considered to be large-scale insect farms, over 80% of farmed insect species in Africa are produced for animal feed, while 15% are for human consumption. In contrast, only 5% of farmed insects are used for both food and feed (Tanga and Kababu, 2023).

The black soldier fly (BSF) (Hermetia illucens L.) is the fastest growing insect farming industry, as shown in the figure.

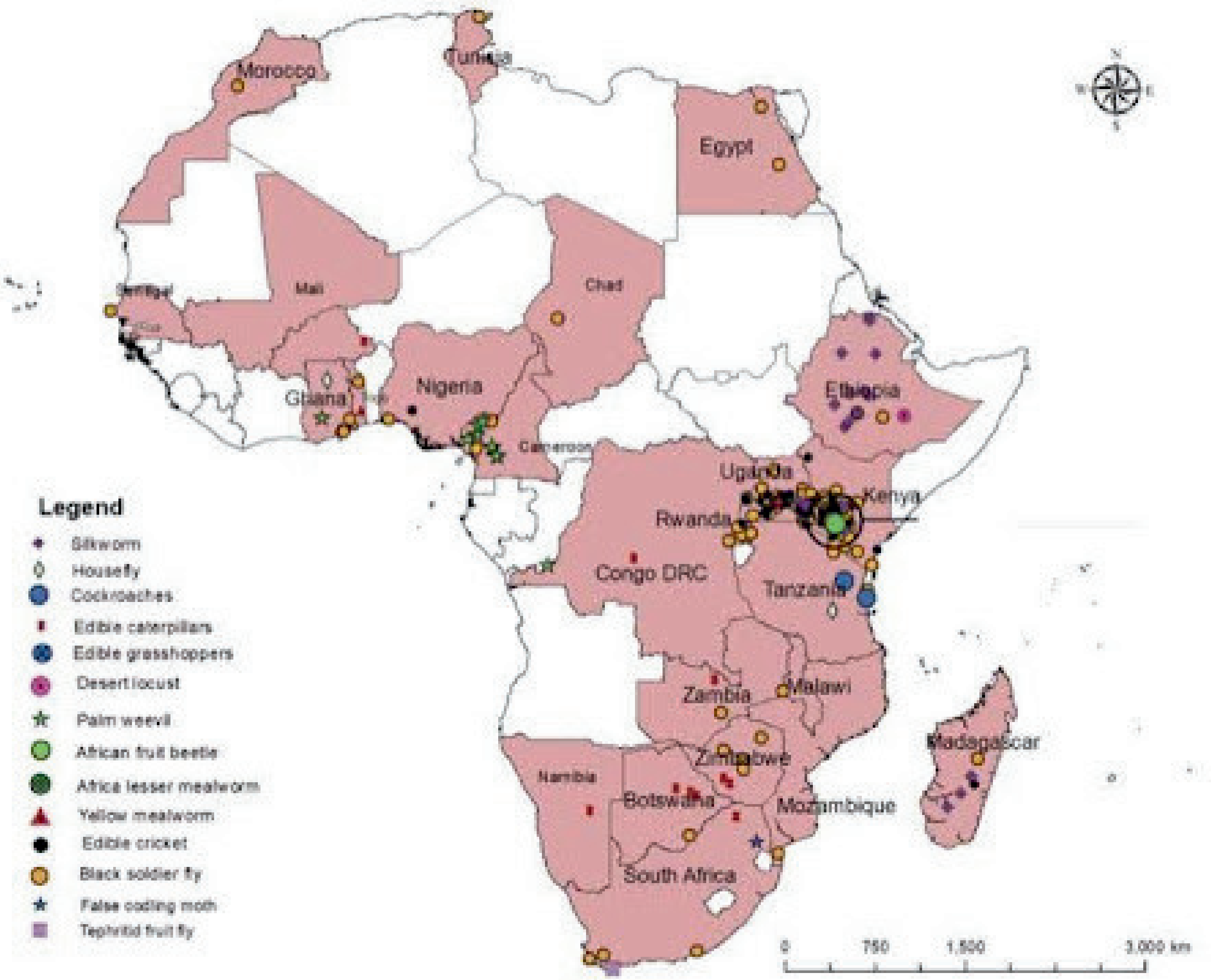


Fig. Distribution of semi-domesticated and domesticated edible insect species in Africa. Countries shaded in white have no insect farming activities and those shaded in brown have operational insect farms for food and feed.

The use of insects as animal feed has been reported in several African countries, including South Africa, Nigeria, Togo, the Democratic Republic of Congo, Angola, Benin and Burkina Faso (Mutungi et al., 2019).

Termites are the insects most commonly used in animal feed in Africa. Several genera, mainly Macrotermes, Odontotermes and Trinervitermes, are traditionally collected or trapped by small-scale farmers in sub-Saharan Africa to provide a source of protein for chickens, guinea fowl or turkeys. This practice has been particularly well studied in West Africa.

In Ghana, a recent survey (Boafo et al., 2019) showed that 42% of traditional poultry farmers frequently feed termites and only 11% never feed termites to their poultry. In a national survey in Burkina Faso (Sankara et al., 2018), 78% of poultry farmers reported providing termites to their poultry, but the rate varied widely by region and province. This practice is also observed in other African regions (Munyuli Bin Mushambanyi and Balezi, 2002; Rutaisire, 2007).

INSECTS AND AQUACULTURE IN AFRICA

Insect meal is a promising alternative to the protein sources currently used in aquaculture feeds because of its high protein (35-61%) and lipid (13-33%) content, as well as other health benefits such as high energy, fat and fibre content, minerals, vitamins, chitin and other macronutrients (Van Huis et al., 2013; Ojha, et al., 2021; Siddik et al., 2024).

It is worth mentioning that, in many cases, insects are part of the main diet of freshwater fish (Ferrer Llagostera et al., 2019), and that many marine fish also feed on crustaceans, which are also arthropods, thus sharing some of their characteristics with insects (van Huis and De Prins, 2013).

Interest in the use of insects as a sustainable and healthy protein source for humans and farm animals has increased in recent years, and insect meal has recently been proposed as another potential alternative (see table 2) to cover protein needs in fish diets in Africa (Kenis et al., 2014; Sspuuya et al., 2017; Tanga and Kababu, 2023, ; Gbai et al., 2024).

Tableau 2 : comparaison des 3 sources de protéines en aquaculture

Characteristics	Fish meal	Soybean meal	Insect meal
Benefits	High nutritional value Palatability	Availability Price	Nutritional Value Palatability Sustainability Nutraceutical Benefits
Disadvantages	Price Sustainability	Anti-Nutritional Factors Lack of palatability Risks related to mycotoxins Sustainability	Profil Acides gras Price Availability

CONSUMERS AND AQUACULTURE PRODUCTS FED WITH INSECT MEAL

Interest in insects as an alternative feedstock for farmed fish has grown as a result of the environmental impact of their production, which is lower than that of conventional feedstuffs due to their short supply chain (Madau et al., 2020), their feed conversion rate and their nutrient content, particularly protein (Barroso et al, 2014; Lock et al., 2018), and are environmentally friendly for aquaculture (Hoffmann et al., 2021), however, the acceptance of insect proteins in aquaculture is not only linked to technical and economic limitations (Smetana et al., 2016), but also to consumer preferences and attitudes (Domingues et al., 2020).

Insects can represent a valuable and cost-effective source of animal feed in Africa. However, many factors, including food neophobia and the social and cultural context, can affect consumer perceptions of food products derived from insect technologies.

Consumer perception of the use of insects in aquaculture feeds is conducted in developed countries, particularly in the European Union (EU) (Maulu et al., 2022, Roccatello e al., 2024). In addition, different cultures and beliefs are likely to affect perception, although further studies are needed to confirm this.

The results of the study conducted in Mali, DRC and Niger (Nguezet et al., 2024) and in Mali, Niger and Ghana (Traore et al., 2024) show that consumers in all these countries agree on the use of insects (Black Soldier Fly: BSF) as animal feed and on the consumption of eggs, fish and meat from animals fed with BSF.

Therefore, further studies are needed in different countries, at least the main producers, and among consumers in different cultures to determine the future of the use of insects in aquaculture feeds.

Wider adoption of the use of insects in aquaculture feeds is likely to depend, to a greater extent, on aquaculture producers and consumer acceptance (Maulu et al., 2022).

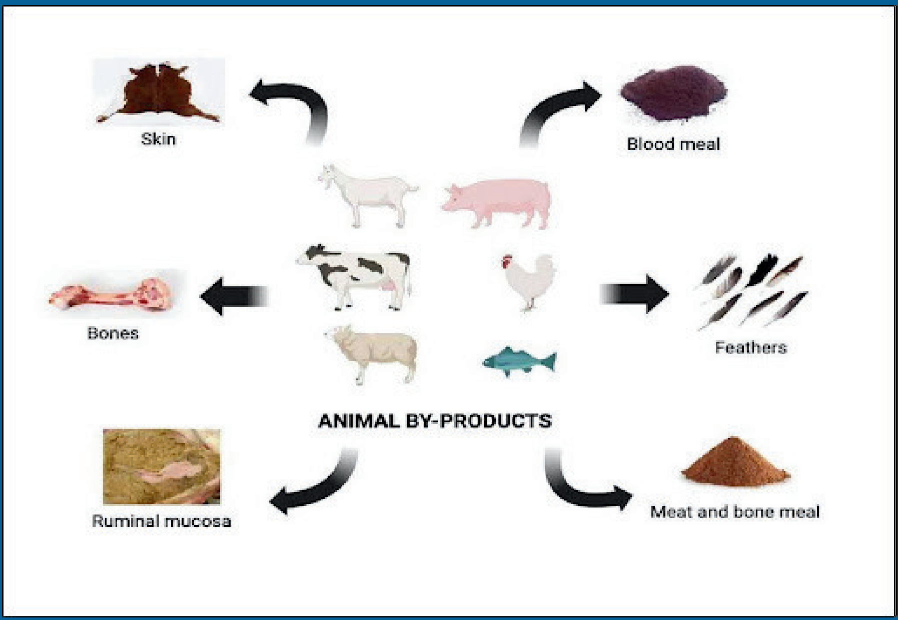
CONCLUSION

The introduction of insect meal as a raw material in nutritional formulations for animal feed and aquaculture in Africa is a reality and opens up new prospects for the production sector, encouraging debate on the sustainability of aquaculture combined with the quality of alternative food products as possible substitutes for high conventional raw materials with greater economic value and environmental impact. Among the insects of interest, the black soldier fly has characteristics that make it viable for application in aquaculture due to its short life cycle, ease of management and ability to transform organic waste into quality protein and lipid biomass, which can positively promote the sustainability of the aquaculture production sector in Africa,

where the use of insect meal is still low and far from being used as the main protein ingredient in the formulation of nutritional compounds for the commercial cultivation of aquatic organisms.

The African insect production sector needs more research and investment at industrial level, but it is emerging as a promising alternative sector for aquaculture nutrition.

ALTERNATIVE PROTEIN SOURCES IN AQUAFEED: CURRENT SCENARIO AND FUTURE PERSPECTIVES



Fish meal represents the main protein source for most commercially farmed aquatic species, as it is characterized by high nutritional value and lack of anti-nutritional factors.

This review aims to comprehensively examine and critically revise the use of fish meal and all alternative protein sources explored to date on the health, welfare, and growth performance of the major aquatic species commercially interesting from a global scenario. However, its availability and the market price have been recognized as serious problems at least for over a decade, making it necessary to search for nonconventional protein sources, as an alternative to fish meals.

1. INTRODUCTION

Agricultural production will need to increase by 50 %, to satisfy the growing demand for food according to the expected increase in the global population (9.7 billion people by 2050) (Hunter et al., 2017). Moreover, the increasing consumption of animal-based foods, and the improvement of the living standards in developing countries, will lead to increased global demand for sustainable animal proteins (Kim et al., 2019).

For these reasons, alternative feed protein sources will be necessary to replace the current supply and satisfy the growing need. To address this need, research is exploring alternative protein sources for feed, as demonstrated by the increasing number of publications on such topics in the monogastric, ruminant, and aquaculture species in the last 10 years (Fig. 1).

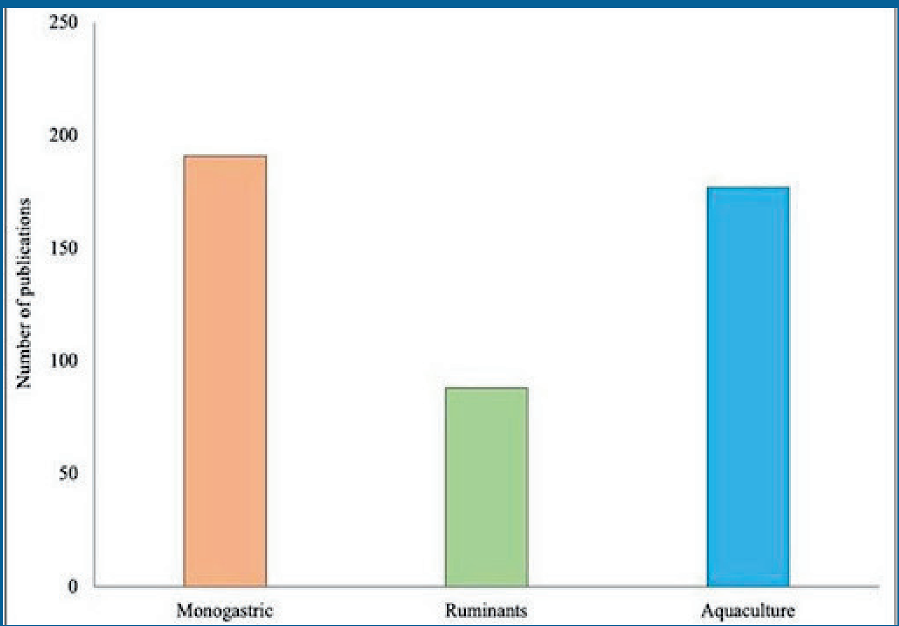


Fig. 1. The number of publications on alternative protein sources in monogastric, ruminants, and aquaculture sectors since 2014.

Aquaculture represents one of the most important sources of animal proteins for human nutrition. Fish grow rapidly and provide adequate calorie-protein ratios for human consumption (Melenchón et al., 2022). Moreover, the increasing demand for seafood, recommended as healthy and sustainable, may be incompatible with ecological sustainability (Teixeira and Silva, 2024). Consumers play a key role, since based on their commercial choices they can promote sustainable fish farming systems, which have now become essential to increase food production as the global population increases.

Many fish reared for human consumption require high protein levels to grow properly, and aquaculture has faced sustainability issues in recent decades.

Fish meal (FM) is considered the ideal protein source in aquaculture, particularly for carnivorous species, because it is rich in protein content, properly balanced with essential amino acid (AA) profile, highly nutritive, and palatable. According to the FAO report (2022), 16 million tons of fish caught (9.03 % of the total) are used directly for the production of FM and oil. The rapid growth of the aquaculture sector has significantly contributed to the increasing demand for FM, which in turn has led to overfishing and subsequent destruction of aquatic ecosystems (Szczepanski et al., 2022). Total feed production for all fish species is estimated to increase by 75 %, from 49.7 million tons in 2015 to 87.1 million tons in 2025 (Hua et al., 2019).

The shortage and the expensiveness of FM have made FM-based feed a limiting factor in the aquaculture industry, leading to the search for alternative sources with high protein content and similar nutritional value (Irm et al., 2022).

Ideal alternatives to FM should be characterized by a suitable AA profile, high nutrient digestibility, and low fiber and carbohydrate content. Moreover, the price should be competitive, the environmental impact low, and the source should be fully available, and easy to use.

Great efforts have been made to find alternatives to FM and among them are terrestrial plant proteins, animal by-products, insect meals, marine algae, and biomass, characterized by a valuable protein content (Fig. 2) (Aragão et al., 2022).

Most likely a combination of different protein sources is better than a single protein source because the mixture has a preferable AA profile, which results in better fish growth performance.

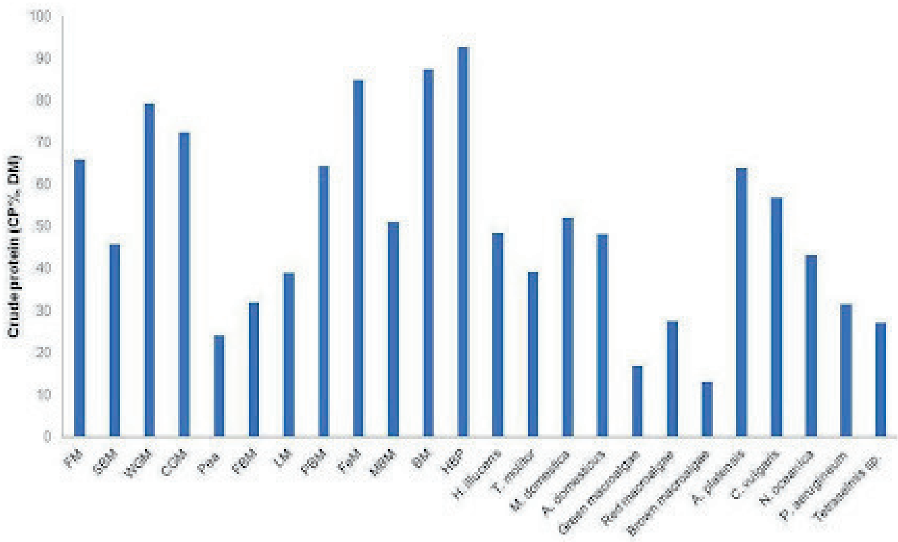


Fig. 2. Protein content (CP %, DM) of suitable alternative protein sources to replace fish meal (FM) in fish diets. FM: fishmeal; SBM: soybean meal; WGM: wheat gluten meal; CGM: corn gluten meal; FBM: faba bean meal; LM: lupin meal; PBM: poultry by-products meal; FeM: feather meal; MBM: meat and bone meal; BM: blood meal; HBP: haemoglobin powder.

The present review aims to comprehensively examine and discuss the use of FM and all alternative protein sources explored to date on the health, welfare, and growth performance of major aquatic species of commercial interest from a global scenario.

This work, evaluating the progress achieved in the last decade, and identifying the most sustainable alternative sources from both economic and environmental views, will help the aquaculture sector to reduce the costs of feed.

Finally, possible future approaches based on innovative alternative protein sources not authorized yet, are also suggested.

2. RESEARCH METHODOLOGY

The present review analyses the scientific papers reporting evidence of using alternative feed protein sources in the aquaculture sector.

A systematic search of the literature was performed in Minerva (access point to the bibliographic resources available from the University of Milan), PubMed, Google Scholar, Scopus-Elsevier, Scifinder-n, and ResearchGate to retrieve all available studies using the following search terms "alternative protein source", and "protein feedstuff" followed by the name of the animal species or zootechnical categories (i.e.: fish including Sparus aurata, larvae, juvenile, etc.), and "aquaculture".

Specific names of the alternative plant-protein sources (i.e. soybean meal, corn/wheat gluten meal, rapeseed, lupin, etc.); specific names of the alternative animal-protein sources (i.e. blood meal, feather meal, Hermetia illucens, Tenebrio molitor, etc.); specific names of the macroalgae/microalgae, and single-cell protein were also searched in the databases. The search delivered a total of about 350 results. Having removed those results nonrelated to the topic, 205 articles were selected.

3. ALTERNATIVE PROTEIN SOURCES TO FISHMEAL

3.1. PLANT-PROTEIN SOURCED FEEDSTUFFS

Plant protein sources are recognized as the main source to replace FM, due to their wide availability, reasonable cost (Kari et al., 2023), and different AA compositions. A range of plant ingredients are used in the aquaculture industry including grains (wheat, corn etc.), oilseeds (soybean, sunflower, rapeseeds, cottonseed, etc.), and pulses (beans, lupins, peas, etc.) (Obirikorang et al., 2020; Kaiser et al., 2022; Burducea et al., 2022; Szczepański et al., 2022; Reis et al., 2019; Ogello et al., 2017).

Despite these positive features, they show significant limitations; Primarily, the presence of anti-nutritional factors (ANFs; phytate, trypsin inhibitors, and lectins for instance), generally affects palatability and interferes with the efficient nutritional utilization of diets, thus leading to alteration of growth performance, immunity, and lead to inflammation processes (Aragão et al., 2022).

No less, it has been reported that ANFs and carbohydrate fractions present in plant-based proteins included in diets may alter the aquatic species' digestion and nutrient utilization (Murashita et al., 2019; Dossou et al., 2021). The use of these protein sources showed contradictory effects on aquatic species. Some studies reported that high levels of dietary plant proteins tend to decrease feed intake (FI) and consequently a worsen growth performance (Sharawy et al., 2016; Kari et al., 2022).

Contrarily, several studies demonstrated that FM replacement with plant proteins did not negatively affect the growth performance of animals (Valente et al., 2016), even reporting an improvement (Kari, 2023), reason why it would be desirable to combine different plant proteins to meet the nutritional needs of aquaculture species.

3.1.1. SOYBEAN AND SOYBEAN BY-PRODUCTS

Soybean (Glycine max, L.) is an annual crop belonging to the Leguminosae family (Dei, 2011). Soybean, and particularly soybean meal (SBM) are the source of plant proteins alternative to FM mostly used in aquafeed.

SBM is an excellent source of balanced AAs (Table 1), rich in lysine (Lys), tryptophan (Trp), threonine (Thr), and isoleucine (Ile), which are often scarce in cereal grains (Florou-Paneri et al., 2014).

Furthermore, soybean by-products (e.g. fermented SBM, soy pulp, soybean protein concentrate) represent a valuable replacement for FM, due to the lower amount of ANFs generated through the fermentation process (Zulhisyam et al., 2020).

3.1.2. CORN/WHEAT GLUTEN MEAL

Corn gluten meal (CGM), a corn starch by-product, represents the main protein fraction obtained from the wet milling process for the separation of the starch, germ, protein, and fiber corn components.

This by-product is characterized by protein content of 67-71 %, low fiber content, and absence of ANFs (Kopparapu et al., 2022); however, is poor in essential AAs such as Lys and Trp.

3.1.3. RAPESEED AND RAPESEED BY-PRODUCTS

Rapeseed (Brassica napus, L.) is one of the most important oil crops in the world, ranking fifth after soy, cotton, peanuts, and sunflower (Lafarga, 2021). It is commonly known as canola (Canadian rapeseed 00 variety) (Kaiser et al., 2022), primarily cultivated for oil extraction, and the meal that remains after this process is a rich source of protein (around 36-50 %) (Thiyam et al., 2004; Muranova et al., 2017). Therefore, it may be used either as a high protein feed supplement especially in cattle, poultry, and aquatic animals, or as organic fertilizer.

However, the presence of ANFs (e.g. glucosinolates, erucic acid, tannins, sinnapine, phytic acid, and indigestible carbohydrates) limits its inclusion level as FM replacer in diets usually not above 10-20 % (Sallam et al., 2021). Despite all treatments applied to reduce ANFs and to increase CP content, rapeseed protein products were only sporadically used to replace FM in aquatic feeds without adverse effects on fish's growth performance (Kaiser et al., 2022).

3.1.4. LUPIN (LUPINUS L.)

Lupin belongs to the Fabaceae family, and the genus Lupinus includes 267 botanical species; however, only four of these are cultivated in different pedo-climatic areas, namely white lupin (L. albus), blue lupin (L. angustifolius), yellow lupin (L. luteus), and pearl lupin (L. mutabilis) (Abraham et al., 2019).

The use of lupin in animal nutrition is not that frequent, due to its low palatability and the presence of ANFs, such as non-starch polysaccharides, oligosaccharides, hemicellulose, cellulose, especially neutral detergent fiber (NDF), and acid detergent fiber (ADF) that affect the nutritional characteristics and reduce the nutrients digestibility (Struti et al., 2020; Parrini et al., 2023).

The protein value of lupin is comparable to the ones of SBM, peas, or other legume grains (Sujak et al., 2006), especially after dehulling (De Vries et al., 2012).

The lupin's hull represents about 15-30 % of the seed weight, and its mechanical removal contributes to an increase in nutritional value in particular in the level of protein (31.1 and 54.4 % DM). Whole lupine seeds are characterized by a variable AA profile, rich in Leucine (Leu), Valine (Val), Thr, Ile, and Serine (Ser), but poor in Trp and sulfur AAs such as Methionine (Met) and Cystine (Cys). In aquaculture, the use of lupin as an FM alternative is still under investigation.

3.1.5. FABA BEAN (VICIA FABA, L.)

Faba bean (FB) belongs to the Fabaceae family and is an annual crop cultivated worldwide, sown in autumn or in spring and, even though primarily grown for its edible seeds (beans), also used as a whole crop.

FB is an important food and feed legume due to the high nutritional value of its seeds, which are plentiful of proteins (25-33 % DM) and starch (40-48 % DM), thus representing a valuable source of protein and energy for livestock (Guevara Oquendo et al., 2022).

Despite being rich in protein, carbohydrates, fats, and minerals, FB seeds contain a variety of ANFs, such as vicine and convicine, well-known to cause the favism syndrome (Rizzello et al., 2016).

3.1.6. PEA (PISUM SATIVUM L.)

Pea belongs to the Fabaceae and Papilionoïdeae phylogenetic group like soybean (Fischer et al., 2020).

Raw peas are relatively low in ANFs compared to dry edible beans, including protease inhibitors, tannins, lectins, and phytate (Iji et al., 2017).

Compared to protein-rich soybeans, peas are legumes with relatively lower protein content, which ranges from 18 to 33 % (Walter et al., 2022).

Nevertheless, with a lower content of sulfur amino acids and less protein digestibility, pea has a lower nutritional value than, for example, soybeans. Moreover, peas contain more AAs involved in off-flavor development, such as Leu (3.5 vs 6.6 g amino acid/100 g protein for pea and soybean), Ser (2.5 vs 4.8 g/100 g protein for peas and soybean), and Thr (1.6 vs 3.6 g/100 g protein for pea and soybean), making them a less appreciated product (Fischer et al., 2020).

Pea is a common FishMeal replacement for marine and freshwater species. Aside from pea meal, a valuable alternative to Fshmeal is represented by pea pods, a food waste of high interest as it is environmentally friendly and able to reduce production costs. Furthermore, pea protein concentrate can be used as an FM protein replacer in fish feed formulation.

3.1.7. OTHER OILSEEDS USED AS FISH MEAL REPLACER

Sunflower meal (SFM) is a by-product that remains in large quantities after the oil is extracted from sunflower seeds.

SFM is a rich source of protein (290-340 g/kg) for fishes, and, due to the price lower than that of SBM and high palatability, it is primarily used as a low-cost protein and energy source for all classes of animals (Banjac et al., 2021; Shi et al., 2023).

The content of sulfur-containing AAs in sunflower flour is lower than in SBM, but other AAs are more balanced, especially glutathione and aspartic acid.

3.2. NON-PLANT PROTEIN SOURCES

3.2.1. ANIMAL BY-PRODUCTS

Animal-sourced feedstuffs for aquaculture derive from the by-products of fish, poultry, pork, and beef, as they are made from several organs or tissues, such as blood, intestinal mucosa, feathers, meat, and bone (Jia et al., 2022)(Fig 3).

These animal by-product meals are considered valuable FM alternatives due to their nutritional quality, including an AAs profile more similar to the one present in the animal, and low prices.

Moreover, they display considerable advantages over plant-derived proteins, such as lack of ANFs.

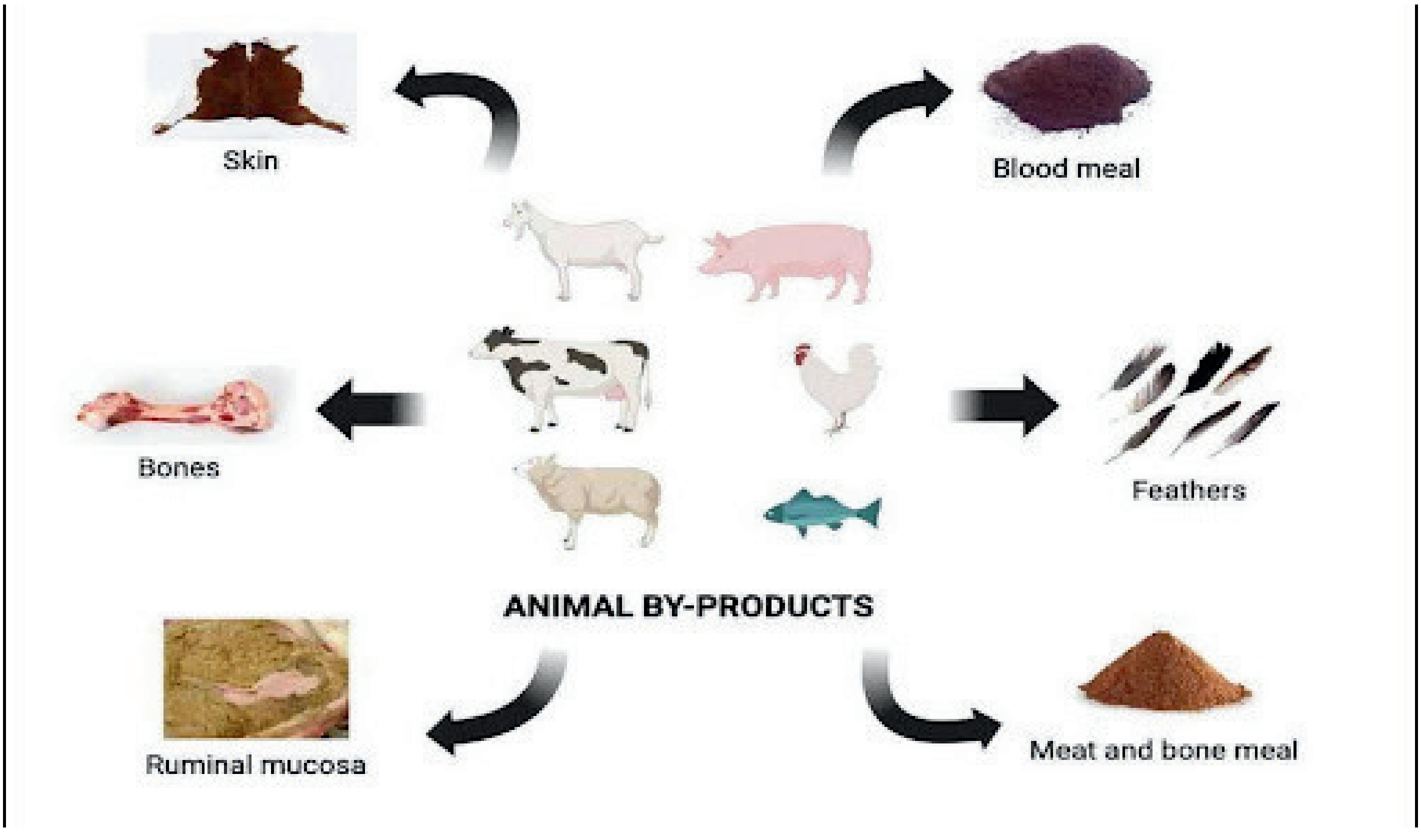


Fig. 3. Main animal by-products used in aquaculture feed formulation.

3.2.2. INSECTES ET INVERTÉBRÉS

Insect farming for the feed industry has increased significantly worldwide (Mulazzani et al., 2021). Among the so-called novel foods are terrestrial invertebrates, including insects and earthworms. It should be noted that, to date, the use of earthworms as feed for monogastric animals and cattle is not permitted if the earthworms are raised on waste (e.g. animal manure, organic fraction of solid urban waste), despite some preliminary findings proving the safety of this procedure (Conti et al., 2019; Tedesco et al., 2020). In contrast, insect meal (IM) can be used in aquaculture nutrition (European Parliament, 2017).

The insects are a feed ingredient with an interesting nutritional profile, since they are rich in AAs, lipids, vitamins, and minerals. Also, the insects are characterized by fast growth and reproduction rates and their requirement of water and land is minimal. For these reasons, the use of insects in fish feed production is considered to be one of the most sustainable and economically viable alternatives (Fisher et al., 2020; Auzins et al., 2024). The frass can also be used as a soil ameliorant (Tedesco et al., 2020; Poveda, 2021; Aragão et al., 2022).

For these reasons, the use of insects as a protein source in fish nutrition represents an attractive alternative to FM and has become one of the main focuses of much research over the last years (Nogales-Merida et al., 2019; Alfiko et al., 2022; Tran et al., 2022).

The Insect Meal (IM) is extremely rich in proteins (60-80 %), essential AAs, vitamins, and minerals, and provides a good source of lipids, due to the lipid content of the insects (31-43 %). It must be pointed out that some technological processes such as drying, fat extraction, or enzymatic hydrolysis, can improve the nutritional value of IMs (Mikołajczak et al., 2020). Up to now, several studies have demonstrated the efficiency of IMs in different fish species as FM replacers.

Among insects, the black soldier flies (Hermetia illucens) are the most studied for nutrition purposes, followed by the yellow mealworm (Tenebrio molitor).

The inclusion of black soldier larvae meal in the diet of several fish species has been evaluated at various inclusion levels without negative effects on growth performance and other physiological responses (Xiao et al., 2018; Wang et al., 2019; Abdel-Tawwab et al., 2020).

It is worth considering that different fish species have different levels of requirement for insects in their diet, which vary according to growth stages and farming systems; to commercialize IM in the future, these requirement levels must be known.

One issue that certainly needs to be considered regarding the future perspectives of IM is consumer acceptance, a necessary prerogative for successful IM supplementation into aquaculture.

This acceptance could be accelerated by making information available for product awareness, starting for example with younger segments of the population, who are more willing to learn new concepts.

The insect industry certainly needs to expand its production scale so it can compete on the price of other more common protein sources, as the production volume of SBM and FM is thousands of times greater.

4. ALGUES MARINES

4.1. MACROALGUES

The Macroalgae, also called Seaweeds, are divided into three large groups based on their color. Green seaweeds, including more than 13,000 species, owe their color to the presence of chlorophyll a and b, which is used during the photosynthetic process.

Red seaweeds (Rhodophyta) comprise 6100 species and their color is due to phycoerythrin and phycocyanin pigments; they contain a higher amount of proteins (up to 47 % of DM) compared to green and brown algae (Carpena et al., 2021). Among macroalgae species, red algae appear to be the most suitable source of animal feed due to their relatively high protein content and structurally diverse bioactive compounds with great pharmaceutical and biomedical potential (Younis et al., 2018). Brown seaweeds (Ochrophyta, Phaeophyceae) include 1800 species and the color is correlated with the content of carotenoid fucoxanthin.

The protein content of the latter is lower than the other two classes, ranging between 5 and 15 % (Mohammed et al., 2021). From a regulatory point of view, within Europe, seaweeds that have been subjected exclusively to drying and crushing are referred to as "seaweed meal" (European Union Commission Regulation, 2022); otherwise, seaweeds subjected to other manufacturing processes are considered "novel feed ingredient", regulated by European Regulation (EC) No. 767/2009.

Marine seaweeds represent a promising alternative to FM due to their low costs and relatively well-balanced essential AA composition.

Over 75 % of seaweed has higher proportions of total essential AAs than wheat flour, 50 % higher than soy flour, and also than rice and corn (Maehre et al., 2014).

The inclusion of macroalgae could improve fish growth performance, or in any case not negatively affect them (Sotoudeh and Mardani, 2019; Zeynali et al., 2020).

It is already known that feeding fish with excessive macroalgae interferes with nutrient utilization and adversely affects growth performance because they have a limited capacity to degrade non-starch polysaccharides (NSP), which are predominant in algae.

4.2. MICROALGAE

Like macroalgae, microalgae could be useful as feed additives or replacements to FM, due to their capacity to synthesize nutrients and therefore produce an added high-value biomass, useful in aquaculture nutrition (Sagaram et al., 2021). As an interesting characteristic, microalgae can grow on some waste, including wastewater, converting organic components in eutrophic effluents into nutrients, including proteins, with well-balanced AA profiles, lipids, and carbohydrates. In particular, they can provide a high percentage of proteins (30-40 %), with a high level of Met, synthesized, for example, in large amounts by the Chlorella, Chlamydomonas, Porphyridium, Isochrysis, and Nannochloropsis genera (Wan et al., 2019). In addition, their typical feature of lack of lignin improves the digestibility in fish (Niccolai et al., 2019).

In aquaculture, numerous studies were conducted on different fish species to test the effect of FM replacement with microalgae. The studies and the reviews published in the last 10 years agree on the evidence that using microalgae in fish diets supports health, survival rate, and growth performance. Particularly, they correlated with an improvement of Feed Ingestion, BW, FCR, and immune response, despite a percentage of inclusion too high could negatively affect these growth performance parameters (Jiang et al., 2019; Nagappan et al., 2021). Moreover, due to the nutritional value of microalgae, the fillet quality characteristics were improved (Nagappan et al., 2021; Ribeiro et al., 2017; Chen et al., 2019a).

5. SINGLE-CELL PROTEIN

Single-cell protein (SCP) refers to proteins extracted from pure or mixed cultures of microorganisms, such as microalgae, yeast, fungi, or bacteria, and can be used as a substitute for conventional protein sources intended for human and animal consumption (Pereira et al., 2022). Other names it can refer to are bioprotein, microbial protein, or biomass (Sharif et al., 2021). Their numerous advantages compared to traditional protein sources (e.g. high crude protein content (60-80 %), shorter production time, less use of land, ability to grow on a variety of substrates, absence of ANFs) have made SCP of particular interest in the aquaculture sector, especially as a valuable substitute for expensive protein sources such as FM and SBM (Ruiz et al., 2023).

To reduce the production costs of SCP, several low-cost suitable substrates have been used so that the microorganisms can grow and produce tons of proteins. Such substrates include waste products from agriculture and industry (e.g. waste of fruit and vegetable processing, brewery wastewater) (Sharif et al., 2021). Although microalgae are part of the SCP group, for the purposes of this review they have been considered together with macroalgae in the previous paragraphs. Over the past 10 years, the use of SCP has been examined in a panel of studies involving the main commercial aquatic species and showed its potential to replace FM and terrestrial plant proteins, especially in the case of yeast, or unicellular fungi (Glencross et al., 2020; Agboola et al., 2021).

6. NEW PROPOSALS FOR ALTERNATIVE PROTEIN SOURCES TO FISHMEAL

Like the animal by-products derived from poultry or livestock used in fish nutrition, crustacean processing discards contain valuable products including proteins, lipids, astaxanthin, organic acids, essential amino acids, chitin, and calcium (Prakash et al., 2012). For example, snow crab processing discards can potentially be recovered from processing industries, and converted into by-products such as crab meal with a higher content of CP and lipids (51 % and 16–25 %, respectively) or recovered for their high content of astaxanthin (33.8–39.6 μg/g) (Burke and Kerton, 2023). Other crustaceous species have returned to the media spotlight for their national interest as invasive species for aquatic ecosystems. This is the case of the blue crabs *Callinectes sapidus* (Rathbun, 1896), *Portunus segnis* (Forskål, 1775), and *Procambarus clarkii* (Girard 1852), known as Louisiana crayfish.

The blue crabs, native to the American coast and Indo-Pacific Ocean, respectively, have established themselves in the Mediterranean Sea (Mancinelli et al., 2021; Marchessaux et al., 2022; Shaiek et al., 2021) and neighboring waters, where they are currently considered an invasive alien species (Zenetos et al., 2005). Furthermore, the areas of expansion include also the Adriatic Sea and the Black Sea. Their biological characteristics such as early sexual maturity, rapid growth rates, opportunist diet, high reproductive rates, generalist habitat use, long-range larval dispersal, and effective physical and aggressive behavior (Castriota et al., 2022; Mancinelli et al., 2017), make blue crab species efficiently invasive and with high potential of successful spread across sea areas.

Additionally, their biological traits imply that they have the potential to impact benthic communities at multiple trophic levels.

7. CONCLUSIONS

The most relevant result emerging from this study consists in highlighting that the alternative ingredients used up-to-date to fully or partially replace FM may affect several health parameters of aquatic species. In general, the inclusion levels of the different protein sources, plant- and animal-derived, ranged from 10 to 80 % and from 2 to 100 % respectively, in full or partial replacement of FM. The parameters positively affected are the growth performance, followed by the improvement of the immune status and antioxidant defense, and consequently a better general health, welfare, and fillet quality. Studies have shown a high variability of the inclusion levels, which could vary depending on the species and time of administration, as well as on the protein source production process. Although replacing FM with plant-based ingredients is considered environmentally sustainable, it should be considered that such a substitution would shift the demand for resources from oceans to land, potentially adding pressure to terrestrial food production systems, and impacting the environment, biodiversity, availability, and prices of crops.

At present, availability and low cost remain the major limitations for the use of several new alternatives in aquaculture feed.

Not all the new protein sources discussed in this review are available for the aquaculture feed industry and their direct use for aquatic feeding may be limited by several factors, including an unbalanced AA profile, a low protein quantity, or the presence of ANFs.

Plant-based by-products are commercially available, but their nutritional value is often too low to meet the nutritional requirements of some aquatic species, making necessary additional processing steps, which would also increase production costs. Animal by-products are commercially available in large quantities and are commonly used as aquatic feed ingredients.

Furthermore, it should be considered that it is unlikely that a single protein source can satisfy the nutritional needs of a certain aquatic species, therefore, it is advisable to mix different protein sources to exploit the nutritional properties of each ingredient, observing synergistic or antagonistic effects. It follows that the future of aquatic feed formulations will probably be based on the blend of different protein sources, both of vegetable and animal origin. However, future research is necessary to determine which alternative proteins are the most suitable, in what proportions they should be included in diets, and how their nutritive value could increase, considering also their environmental impact.

The other main global issue that aquaculture is expected to face in the future is the progressive growth of the sector, which will have to satisfy the increasing demand for protein from an expanding global population. The aquaculture industry is large and complex and can include the possible farming of more than 650 species of fish, shellfish, aquatic plants, and algae grown in a variety of marine, brackish, and freshwater systems.

However, to consider these sources cost-effective and above all sustainable for their use in the future, other factors should be taken into account, such as feed cost, costs of the farming system, and finally Life Cycle Assessment (LCA). Therefore, further efforts are still needed to find cost-effective ways to introduce alternative diets, ensuring both economic and environmental sustainability.

Source : Serra V, Pastorelli G, Tedesco DEA, Turin L, Guerrini A. Alternative protein sources in aquafeed: Current scenario and future perspectives. Vet Anim Sci. 2024 Jul 25;25:100381. doi: 10.1016/j.vas.2024.100381. PMID: 39280774; PMCID: PMC11399666.

EXPLORING SUSTAINABLE ALTERNATIVES IN AQUACULTURE FEEDING: THE ROLE OF INSECTS

The aquaculture sector faces uncertainty due to environmental changes, economic factors, and availability of food resources. Conventional aquatic feeds heavily depend on fishmeal, which has driven the search for innovative and sustainable alternatives, such as insects.

These insect-based protein sources have several benefits, such as efficient nutrient utilization, short maturation periods, and profitability, addressing the economic and environmental challenges associated with conventional aquafeed ingredients.

Scientific studies indicate that insects have the potential to improve flesh quality, strengthen the immune system, and reduce disease susceptibility in farmed fish, promoting sustainable and productive aquaculture systems.

The integration of insects as alternative protein sources in aquatic feeds can offer a promising path towards sustainable and environmentally friendly aquaculture systems.

1. INTRODUCTION

The rapid growth of the global human population (1.6 percent per year) has exerted tremendous pressure on the food sector (Gras et al., 2023). With the declining availability of wild fish and crustaceans, aquaculture becomes a crucial protein source for both humans and animals (Alfiko et al., 2022).

The quality and composition of feeds constitute critical factors in aquaculture, impacting animal growth significantly (Xiao et al., 2018). Furthermore, the overexploitation of oceans results in unsustainable pressure on wild fish stocks, resulting in their rapid decline (Daniel, 2018, Stankus, 2021).

In the coming years, this won't be a viable source from sustainability and economic perspectives (Gasco et al., 2018).

The increase in price and scarcity of these raw materials intensify the need to reduce their incorporation percentage and seek more sustainable and cost-effective alternatives in feeds while ensuring the quality and nutritional value of fish (Daniel, 2018, Stankus, 2021).

Fishmeal (FM) in aquaculture has frequently been replaced with plant proteins, with soybean being favorite due to its cost effectiveness and nutritional value (Hameed et al., 2022).

However, the addition of high quantities of soybean meal in the fish diet has been negatively linked to growth, gut and liver integrity, intestinal microbiota composition, and immunological response in various carnivorous fish species (Aragão et al., 2022, Macusi et al., 2023; Y. ru Wang et al., 2017). Consequently, the researchers were forced to develop aquafeeds with innovative feed ingredients that can replace FM while mitigating the negative impacts associated with vegetable protein (Alfiko et al., 2022).

In this context, insects may be a feasible alternative to FM, offering nutritional constituents more similar to FM and, therefore, presenting a promising solution for sustainable aquaculture in the near future (Alfiko et al., 2022). A wide range of insect species have been studied and used in aquaculture to prepare feed ingredients (Barroso et al., 2014). Among those approved by European regulations, Hermetia illucens, Tenebrio molitor and Musca domestica stand out due to their high nutritional value.

Whole insects contain 42–63.3 % crude protein on a dry matter basis (Alfiko et al., 2022), with up to 74 % reported for defatted insect meal (Alfiko et al., 2022).

Beyond the high percentages of protein, nutritional value includes an additional well-balanced essential amino acid (EAA) profile, high lipid content (10–30 %), a good source of vitamins such as vitamin B12, and bioavailable minerals such as iron and zinc (Alegbeleye et al., 2012, Gasco et al., 2020).

Despite the potential and beneficial aspects of using insects in aquaculture, as this is an emerging sector, some limiting factors must be considered. Insect feeding substrates should be standardized, since their composition impacts the nutritional composition of the protein obtained (Sogari et al., 2023).

Likewise, the percentage of conventional protein sources that could be replaced by insect ingredients need to be defined (Van Huis et al., 2021) for different fish species.

The selling price of insect meals can be influenced by several factors, such as the production system, the substrate used and the country where the production unit is located (Niyonsaba et al., 2021).

But also by health benefits associated with bioactive compounds such as antimicrobial peptides, medium chain fatty acids and chitin in their derived forms (Borrelli et al., 2021).

2. GLOBAL AQUACULTURE MARKET

In 2020, global production of aquatic animals was approximately 178 million tons, with the total production predicted to reach 202 million tons by 2030 (FAO, 2022). Over 157 million tons (89 %) were allocated for human consumption, while the remaining 20 million tons were used for non-human food purposes, with about 16 million tons for FM and oil production. The production value of fishing and aquaculture in 2020 was estimated at 367 billion euros, of which 239 billion euros came from aquaculture (FAO, 2022). Global aquaculture is unevenly distributed, with Asia being the main producer, representing, in 2020, 91.6 % of global production (and 85 % of the value).

China is responsible for 56.7 % of global aquatic animal production and 59.5 % of algae production (Mair et al., 2023). The Americas, Europe and Africa represent, respectively, 3.6 %, 2.7 % and 1.9 % of global production. It is often cited that aquaculture represents the fastest growing food production sector in recent decades, with an average annual growth rate of 6.7 % over the last three decades (Mair et al., 2023). Aquaculture contributed to a total of 122.6 million tons in live weight. Around 87.5 million tons were aquatic animals, primarily intended for human consumption, 35.1 million tons were algae, and 700 tons were shells and pearls.

Over the coming years, the average annual growth rate of aquaculture is expected to decrease from 4.2% in 2010-2020 to 2.0% in 2020–2030 tons (FAO, 2022).
However, the sector's evolution is difficult to predict.

The upcoming decade is poised to undergo substantial transformations in environmental conditions, resource accessibility, macroeconomic landscapes, international trade regulations, tariffs, and market dynamics.

These shifts have the potential to impact production, markets, and trade over the medium term.

Climate variability and its changing patterns, encompassing the rise in extreme weather occurrences, are expected to exert noteworthy and varied geographical effects on the availability, processing, and trade of aquatic goods. This situation might render nations more susceptible to risks.

Nevertheless, adept governance that advocates for stringent fisheries management practices, responsible expansion in aquaculture, and advancements in technology, innovations, and research can help alleviate these risks (Engle and van Senten, 2022).

3. CONVENTIONAL AQUAFEEDS AND ITS CHALLENGES

Aquaculture stands as a pivotal force in global food production, experiencing substantial growth. However, this expansion comes with notable challenges, particularly in the realm of conventional feeding practices. A central concern is the widespread reliance on FM as a primary source of proteins and lipids in aquafeeds, primarily derived from wild fish catches (Abdel-Tawwab et al., 2020; Alfiko et al., 2022; Basto et al., 2021). The sheer magnitude of this reliance is underscored by the allocation of approximately 21 million tons of fish, with 76% directed towards aquafeed production, exerting immense pressure on wild fish stocks for non-food purposes (Iaconisi et al., 2018).
FM's popularity in aquafeeds is rooted in its well-balanced amino acid composition and high digestibility. These attributes are crucial for nutrient uptake, digestion and the absorption of essential nutrients, especially in extensively farmed carnivorous fish species such as trout, salmon, seabass and seabream (Abdel-Tawwab et al., 2020, Iaconisi et al., 2018). However, the escalating demand for FM poses substantial challenges to the sustainability and profitability of the aquaculture industry (Alfiko et al., 2022).

The unprecedented growth of aquaculture intensifies the demand for FM, leading to a rapid decline in wild fish stocks (Alfiko et al., 2022; Stankus, 2021). The associated costs of aquafeeds, where FM constitutes a major expense, hinder the industry's sustainable development (Alfiko et al., 2022). In light of the imperative for green, profitable, and sustainable (GPS) production, a revaluation of protein sources with comparable nutritional components is essential (Daniel, 2018).
Plant-based materials, such as soybeans, oil seeds and cereal gluten, are increasingly being used as an alternative for animal feed. However, replacing animal-based proteins with plant-based alternatives is not feasible with the aquaculture industry. Plant-based feeds contain a wide variety of anti-nutritional factors, non-starch polysaccharides, less suitable fatty acid, unbalanced essential amino acid profiles (lysine and methionine), and low palatability. Furthermore, the vegetable alternatives used may involve competition with other sectors in the food industry for both humans and animals.

The global scarcity and high prices of these commodities amplify the urgency to find eco-friendly alternatives (Stankus, 2021).

Moreover, ethical concerns emerge as fish suitable for direct human consumption are allocated for FM production (Stadtlander et al., 2017).

FM, as a finite resource, cannot guarantee a continuous supply of cheap protein for aquafeeds (Ng et al., 2001). Certain aquaculture practices, particularly those utilising wild pelagic fish, contribute to marine ecosystem disruption during FM production (Hashizume et al., 2019).

The future of aquaculture hinges on innovative and sustainable alternatives, such as insects, to address the ecological, economic and ethical dimensions of conventional feeding practices.

For such there is a need to acknowledge the legislation regarding the use of insects as a source of protein for aquafeeds.

4. LEGISLATION

European feed regulations have imposed strict restrictions on the use of animals as feed ingredients, due to the history of bovine spongiform encephalopathy (EC/999/2001; EC, 2001). Nevertheless, a significant change occurred in 2017 with the introduction of Regulation (EU) No 2017/893, which amended Regulations (EC) No 999/2001 and (EU) No 142/2011. This amendment marked a pivotal moment as it allowed the inclusion of seven insect species in the diet of aquaculture animals Hermetia illucens (HI), Musca domestica (MD), Tenebrio molitor (TM), Alphitobius diaperinus (ADi), cricket Acheta domesticus (AD), Gryllodes sigillatus (GS) and Gryllus assimilis (GA). In the future, the revision of this list can be based on a risk assessment of insect species, considering their potential impact on health and the environment.

Regulation (EU) No 2017/893 removed the condition for reared insects that 'products of animal origin must be sourced from a registered slaughterhouse'. This adjustment was essential because insect rearing facilities, where the insects are generally 'slaughtered', faced challenges in meeting the specific requirements applicable to traditional slaughterhouses. Regulation (EU) No 2019/1981 introduced a designated list of third countries that gained authorization to export insect products in accordance with the aforementioned Regulation (EU) No 2017/893. Finally, in November 2021, through Regulation (EU) 2021/1925, the EU legislator officially approved the use of Bombyx mori (BM) in aquaculture.

This decision marked an expansion of the list from seven to eight authorized species. Consumer acceptance is not an issue for incorporating insects in animal feed in Europe (Stamer, 2015). In a Belgian study, findings from cross-sectional data amongst farmers, stakeholders and citizens showed that attitude towards the concept of using insects in animal feed was generally positive, particularly for applications in poultry and fish nutrition as indicated by Verbeke et al. (2015).

To foster the growth of the industrial production of insects and their use as feed in developed and developing countries, significant legislative changes are imperative in the future. Currently, two problems arise concurrently with this expansion, the first concerns the lack of local regulations, while the second concerns the lack of a stable and consistent set of regulations across international borders. More specifically, numerous local companies are interested in exporting their insect products globally, but the regulatory demands and discrepancies between countries complicates the initiatives to market and sell insect products. Additionally, within the European legal framework, constrains persist regarding the substrate options on which insects can be reared, limited to raw materials also approved for other livestock species. Overcoming these barriers requires revising current regulations to accommodate the needs and potential of the insect farming sector.

5. INSECT MEAL QUALITY AND SAFETY

The evaluation of the safety and quality in insect-based feed in aquaculture involves a comprehensive and multidimensional process, including microbial, chemical, and allergenicity analyses, along with assessments of nutritional content and digestibility. As conventional feed sources face limitations, there is growing interest in alternative protein sources, with insect-based feed emerging as a promising candidate. Insects can be reared on organic substrates, contributing to the circular economy and reducing the environmental impact of aquaculture operations (Maroušek et al., 2023).

Moreover, insects are rich in protein, essential amino acids, and micronutrients, making them an attractive source of nutrition for aquaculture species. Some insects also contain beneficial unsaturated fatty acids such as oleic and linoleic acid (Gasco et al., 2019). However, insects lack certain n-3 polyunsaturated fatty acids (n-3 PUFAs), such as the eicosapentaenoic and docosahexaenoic acids (EPA and DHA), crucial for marine fish feeds.

These fatty acids are associated with various health benefits for humans (Lands, 2014), including cardiovascular health (Harris, 2007, Lu et al., 2011), inflammation prevention (Calder, 2008, Fetterman and Zdanowicz, 2009, Figueras et al., 2011), anti-aging effects (Dyall et al., 2010), insulin resistance (Kalupahana et al., 2010), and slows the progression of certain cancers (Astorg et al., 2004, Leitzmann et al., 2004, Westheim et al., 2023).

Table 1. Main nutritional components (%) of three insect species, soybean meal and fishmeala.

	Species				
Nutritional Constituents	*Hermetia illucens* larvae (HIL)	*Musca domestica* maggot meal (MDM meal)	*Tenebrio molitor* (TM)	Soymeal	Fishmea (FM)
Crude protein	42.1	50.4	52.8	51.8	70.6
Lipids	26.0	18.9	36.1	2.0	9.9
Ash	20.6	10.1	3.1	8.5	13.4
Calcium	7.56	0.47	0.27	0.39	4.34
Phosphorus	0.90	1.6	0.78	0.69	2.79

Table 2. Amino acid composition (g/16 g nitrogen) of insect meals, soybean meal and fishmeal

Nutritional Constituents		Species: *Hermetia illucens* larvae HIL)	*Musca domestica* maggot meal (MDM meal)	*Tenebrio molitor* (TM)	Soymeal	Fishmeal (FM)
Essential amino acids	Histidine	3	2.4	3.4	3.1	2.4
	Isoleucine	5.1	3.2	4.6	4.2	4.2
	Leucine	7.9	5.4	8.6	7.6	7.2
	Lysine	6.6	6.1	5.4	6.2	7.5
	Methionine	2.1	2.2	1.5	1.3	2.7
	Phenylalanine	5.2	4.6	4	5.2	3.9
	Threonine	3.7	3.5	4	3.8	4.1
	Tryptophan	0.5	1.5	0.6	1.4	1.0
	Valine	8.2	4	6	4.5	4.9
	Alanine	7.7	5.8	7.3	4.5	6.3
Non-essential amino acids	Alanine	7.7	5.8	7.3	4.5	6.3
	Arginine	5.6	4.6	4.8	7.6	6.2
	Aspartic acid	11	7.5	7.5	14.1	9.1
	Cystine	0.1	0.7	0.8	1.38	0.8
	Glutamic acid	10.9	11.7	11.3	19.9	12.6
	Glycine	5.7	4.2	4.9	4.5	6.4
	Proline	6.6	3.3	6.8	6.0	4.2
	Serine	3.4	3.6	7	5.2	3.9
	Tyrosine	6.9	4.7	7.4	3.4	3.1

While the insect species intended for feed generally do not pose an imminent risk to aquaculture animals, the major risk was identified as originating from the rearing substrate used in insect farming (Maroušek et al., 2023). Substrates contaminated with mycotoxins or heavy metals can adversely affect insect survivability and growth performance.

Accumulation of mycotoxins in insects is not observed so far, but further research is needed, because literature data is very limited (Schrögel and Wätjen, 2019). Contrary, metal accumulation varies depending on metal type, insect species, and developmental stage. Literature indicates that H. illucens (HI) is capable of significantly accumulate cadmium, whereas the Tenebrio molitor (TM) tends to accumulate arsenic in its larval body (Malematja et al., 2023). Regarding the rearing substrate, consistent monitoring of contaminants is an essential aspect for feed security. Considering that certain insects can transform organic waste into valuable biomass, the ban of using waste streams in animal feed, according to EU regulation, may be reconsidered in the future, particularly concerning the special case of insect farming for feed. Additionally, the existing EU limits for contaminants, such as heavy metals in animal feed, may require adjustments based on species-specific accumulation behaviour. Beyond assessing mycotoxins and heavy metals, a comprehensive safety evaluation of microbial hazards, chemical hazards (considering contamination with pesticides and veterinary medicines), as well as the allergenic potential of edible insects and derived products, must be conducted for each insect species (Precup et al., 2022, Schrögel and Wätjen, 2019).

Several studies indicate that replacing FM with insect meal, either partially or completely, has no adverse effects in immune-related parameters, including blood biochemical composition, histopathology of relevant organs, gut health, gene expression and disease resistance in numerous aquaculture species (Fawole et al., 2020, Sankian et al., 2018, Su et al., 2017, Zarantoniello et al., 2020).

The application of plant-based protein, particularly soybean meal, in aquaculture has diminished due to its association with causing intestinal enteritis (Kumar et al., 2021). Notably, in rainbow trout, the inclusion of HI meal in soybean meal-based diets has effectively prevented soybean meal-induced intestinal enteritis (Kumar et al., 2021). According to Xiang et al., (2020), insect meal contains bioactive peptides, potentially contributing to the prevention of this disease. However, the precise mechanism through which insect meal prevents soybean meal-induced enteritis in fish remains unclear and further investigations is required to characterize the bioactive peptides present in insect meals.

6. INSECT SPECIES USED IN AQUAFEEDS AND THEIR NUTRITIONAL COMPOSITIONS

MOST COMMONLY USED INSECTS IN AQUAFEED

Among the insect species tested for industrial aquafeed production, eight stand out as the most promising: HI, MD, TM, Alphitobius diaperinus, Acheta domesticus, Gryllodes sigillatus, Gryllus assimilis and BM (Fig. 1) (Alfiko et al., 2022). However, in this article we will focus on the use of HI, TM and MD as a partial or total replacement of FM (Fig. 2).

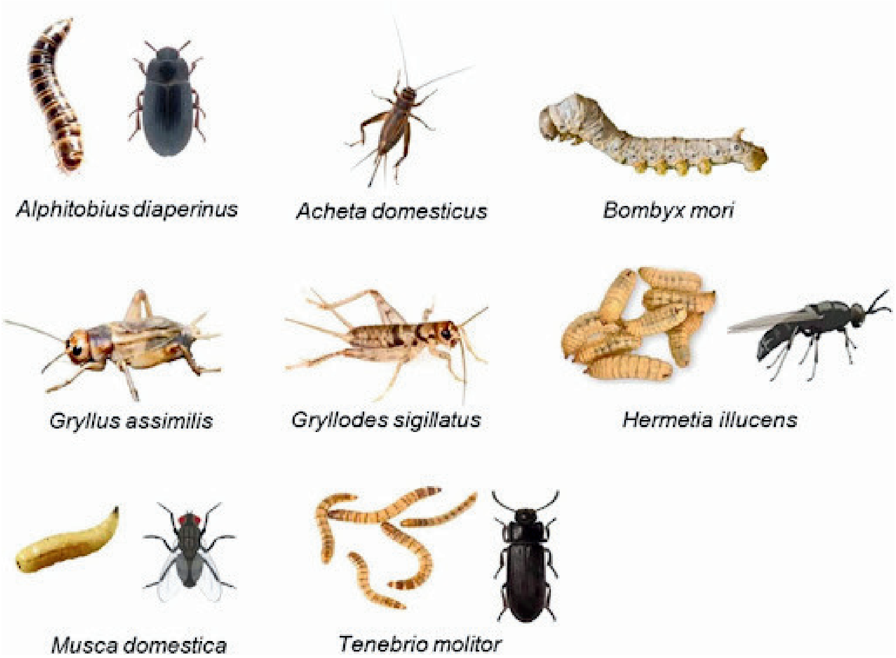


Fig. 1. Eight important insect species for replacing fish meals in aquafeed.

Fig. 2. The most relevant insect species for fish meals: H. illucens, M. domestica and T. molitor.

6.1.1. BLACK SOLDIER FLY (HERMETIA ILLUCENS)

H. illucens larvae (HIL) exhibit exceptional characteristics that make a valuable resource for sustainable animal feed and water valorisation. Their ability to feed on diverse organic matter, coupled with a short maturation period of approximately three weeks, positions them as an efficient and sustainable source (Sheppard et al., 2002, Tomberlin and Sheppard, 2002). The pre-pupa stage of HIL simplifies the harvesting process, eliminating labour-intensive steps and enhancing their suitability for large-scale farming (Sheppard et al., 2002, Mohan et al., 2022). These advantages make HIL a promising candidate for sustainable aquafeeds and waste management, aligning with the principles of green and efficient resource utilization (Čičková et al., 2015, Romano et al., 2022; Y. S. Wang and Shelomi, 2017). Feeding trials involving HIL meal supplementation in various fish species have shown positive impacts on growth performance and feed consumption.

Research demonstrates the potential to enhance the cardioprotective characteristics of fish fillets through tailored insect fatty acid profiles, further emphasising the versability and adaptability of HIL in aquafeeds (Bruni et al., 2020). The integration of HIL into the diets of carnivorous fish, including yellow catfish (Pelteobagrus fulvidraco), rainbow trout (Oncorhynchus mykiss), Atlantic salmon (Salmo salar L.), and European seabass (Dicentrarchus labrax), shows promising results as an alternative to FM. Partial substitution with HIL meal sustains growth performance and positively influences fillet composition and consumer acceptance (Abdel-Tawwab et al., 2020, Hu et al., 2017, Moutinho et al., 2021, Renna et al., 2017, Stadtlander et al., 2017). For Atlantic salmon, complete replacement of FM with HIL meal does not compromise fillet quality (Bruni et al., 2020).

In contrast, studies on omnivorous fish, such as Jian carp (Cyprinus carpio), reveal that while inclusion of dried HIL meal up to 75 % has no adverse effects on voluntary intake or growth, caution is needed at higher substitution due to signs of dietary stress and intestinal damage (S. Li et al., 2017).

Careful selection of substitution levels is crucial for both carnivorous and omnivorous fish to ensure optimal growth performance and minimize potential adverse effects.

Ongoing research is needed to explore long-term effects, optimize diet formulations, and understand the specific adaptation of different fish species to HIL-based diets.

Regarding the topic of waste management, a recent research investigation delved into the potential of Black Soldier Fly larvae to convert aquaculture solid waste (ASW) into biomass (Rossi et al., 2023).

While these are first steps, and further studies are obviously needed to clearly understand the microbial and chemical safety of insects produced on ASW, they open the way for a potential circular economy for aquaculture feeding based on insects.

6.1.2. YELLOW MEALWORM (TENEBRIO MOLITOR)

Feeding trials within the field of aquaculture have substantiated compelling evidence supporting the acceptance of fresh and dried TM as an alternative protein source (Alfiko et al., 2022).

Responding to the escalating demand for sustainable aquafeed solutions, TM meals have emerged as substitutes for traditional FM, prompting extensive studies to assess their efficacy and integration into aquaculture practices (Terova et al., 2021). Numerous investigations have explored the use of TM meals in aquafeeds. Despite a predominant focus on growth effects resulting from the substitution of FM with mealworm meals, a significant knowledge gap persists concerning the underlying mechanisms governing these effects. To address this gap, a critical imperative is to delve into the true modes of action, digestion, and absorption of TM meal within the digestive systems of diverse aquaculture species. Employing molecular genetics and genomic approaches becomes pivotal in unravelling the intricate processes at play (Roncarati et al., 2015; Terova et al., 2021).

This understanding is crucial for optimizing the utilization of TM meals in aquafeeds, ensuring both the efficacy of the substitution and the well-being of the aquaculture species.
Future research endeavors should focus on exploring the untapped nutritional potential of Tenebrio molitor as a novel raw ingredient for aquafeeds (Roncarati et al., 2015). Determining the optimal level of TM meal inclusion that does not impair fish growth performances is essential for facilitating the integration of TM meals in aquaculture practices with maximal efficiency and minimal adverse effects. These comprehensive investigations are indispensable for advancing the sustainable and nutritionally balanced evolution of aquafeeds.

6.1.3. HOUSEFLY (MUSCA DOMESTICA)

The utilization of MD as a supplementary feed for fish has been predominantly investigated within tilapia and catfish species, along with various aquaculture species (Alfiko et al., 2022). Diverse feeding trials conducted across multiple aquaculture species have consistently demonstrated the positive impact of incorporating maggot meal (MD, MDM meal) into fish diets, resulting in enhanced growth and feed conversion ratio while mitigating physiological stress.

Furthermore, the incorporation of MDM meal into fish diets has proven to be a cost-effective strategy, reducing overall feed costs. Considering factors such as nutritional value, availability, growth and feed efficiency, MDM meal emerges as a viable alternative protein source with the potential to replace FM in aquafeeds. This substitution is particularly advantageous in developing countries, where the importation of FM entails significant costs.

Considering factors such as nutritional value, availability, growth and feed efficiency, MDM meal emerges as a viable alternative protein source with the potential to replace FM in aquafeeds. This substitution is particularly advantageous in developing countries, where the importation of FM entails significant costs.

Future research efforts should concentrate on determining the optimal inclusion levels of MDM meal as a substitute for FM, delving into the potential economic benefits associated with such replacement (Alfiko et al., 2022).

In a broader context, the cumulative findings from the studies suggest that MDM meal holds promise as a viable and sustainable alternative to FM across diverse fish diets, contributing to robust growth performance and efficient nutritional utilization.

These results underscore the importance of meticulous consideration and optimization of the inclusion levels of MDM meal in dietary formulation.

6.2. NUTRITIONAL COMPOSITION

The significance of an optimal nutritional composition for enhancing production parameters in aquaculture is widely recognized. Recently, an increasing number of feeding trials have been performed using insect meals to replace partial FM in aquaculture species. Overall, the majority of experiments have demonstrated promising outcomes when replacing a part of FM with insect meals, albeit with variations depending on the fish and insect species involved. However, it appears that replacing more than 30 % of FM with insect meals has resulted in a reduction in fish growth, as indicated by studies conducted by Hua (2021) and Liland et al. (2021).
Insect meal production is developing rapidly in China, Europe, North America, Australia and Southeast Asian countries (Henry et al., 2015; Nogales-Mérida et al., 2019). It is widely known that the nutritional composition of insects depends on rearing substrates, and their fatty acid profile reflects their diet. Enriching insect substrates with these fatty acids can positively modify the insect fatty acid profile (Liland et al., 2017). Nutritional analyses, including crude protein, amino acids, fat content, fatty acid profiles and minerals, have been conducted on eight insect species mentioned above (Sánchez-Muros et al., 2014). Details information on the nutritional components of each insect species can be found in several published reports (Allegretti et al., 2017, De Souza-Vilela et al., 2019). This summary focuses on three key insect species – HI, MD and TM – highlighting their major nutritional compositions.

These three insect species exhibit a substantial crude protein (CP) level ranging from 42.1 % to 60.7 % as indicating in Table 1 . Although, this level of CP is lower than that found in FM, but is similar to soybean meal (Allegretti et al., 2018; Henry et al., 2015). Amino acid profiles vary among the insect species, with TM CPs containing less lysine compared to FM, while Diptera (HI and MD) CPs are notably rich in lysine. Sulphur amino acid contents in insects are lower than in FM. Threonine levels are similar among three insect species as shown in Table 2 (Henry et al., 2015; Sánchez-Muros et al., 2014). Tryptophan levels in the other two insect species, except for MD maggot (MDM) meal, are generally lower, suggesting potential supplementation with synthetic amino acids for optimal growth, depending on the specific requirements of the fish species. Diptera present superior amino acid profiles compared to soymeal (Table 2), making them preferable alternatives for replacing FM in aquafeeds (Henry et al., 2015; Sánchez-Muros et al., 2014). All three insect species have higher fat content than FM, ranging from 18.9 % to 36.1 % (van Huis, 2020). Insects tend to accumulate fat, particularly in their embryonic stages.
The fat content varies across different species, and even within a species, there is a considerable variation influenced by factors such as developmental stage and diet (Barros-Cordeiro et al., 2014, Barroso et al., 2019).

In comparison to fish oil, insect meals have lower amounts of omega-3 fatty acids, with a notable presence of saturated fatty acids (Makkar et al., 2014).

TM and MDM meals exhibit higher concentrations of unsaturated fatty acids, while in Hermitia illucens larvae (HIL) have a lower unsaturated fatty acid content (Gasco et al., 2020, Hawkey et al., 2021, van Huis, 2020). The lipid contents and fatty acid profiles in insect meals are well-recognized to be heavily influenced by their diet, and altering the substrate composition can bring about changes in these aspects (Makkar et al., 2014).

It is crucial to note that the fatty acid composition is affected by several factors, including insect feeds, culturing conditions and the stage of insect harvest.
The ash content of the three insect species is minimal, except HIL, which exceeds 15 %. HIL contains relatively higher calcium, constituting 7.6 % of dry matter, whereas other insect species exhibit very low calcium levels (Table 1).

Therefore, when substituting FM with insect meals, it is essential to include calcium in aquafeeds. Enhancing the calcium content in insect larvae meals can be achieved through the fortifying the rearing substrate with calcium (Allegretti et al., 2017, De Souza-Vilela et al., 2019; Henry et al., 2015; Sánchez-Muros et al., 2014).

Additionally, it is noteworthy that MDM meal exhibits notably high phosphorus levels at 1.6 %. Across the three??? mentioned insect species, carbohydrates levels are generally low (less than 20 %) (Barroso et al., 2014).

The substitution of FM with insect meals faces certain limitations. Depending on the insect species used, it becomes necessary to supplement various nutritional components in aquafeeds.

This supplementation is essential to ensure the optimal nutritional characteristics of fish fillets suitable for human consumption.

Insects, the most diverse group of animals, have garnered attention as natural and nutritious feed sources for fish, particularly carnivorous and omnivorous species with high protein dietary requirements (Alfiko et al., 2022; Nogales-Mérida et al., 2019; Tran et al., 2015; van Huis, 2019).

In the pursuit of sustainable aquafeed solutions, 11 insect species have been evaluated as alternative protein sources, with notable success in recent studies (Henry et al., 2015; Nogales-Mérida et al., 2019).

The replacement of substantial portion of FM with insect-based protein sources has the potential to significantly reduce the FM content in organic aquafeeds.

This not only addresses the economic feasibility of aquaculture but also contributes to the overall sustainability of aquafeed production (Stadtlander et al., 2017).

Moreover, insects represent a promising alternative within the context of a circular bioeconomy.

Aligning with the principles of sustainability and resource efficiency (Bruni et al., 2020).

6.3. CHITIN CHALLENGE IN DIGESTIBILITY

Various studies have underscored the significant nutritional value of insects, emphasizing their considerable potential. The protein fraction, accounting for 40–60 % of dry weight, and the balanced amino acid composition reinforce the relevance of these insects, suggesting that their flours can entirely or partially replace FM in aquaculture feeds (Gasco et al., 2020, Makkar et al., 2014).

However, a challenge and point of discussion in the scientific community lie in the significant presence of chitin and the associated antinutritional effects.

Chitin, the second most abundant polysaccharide on Earth after cellulose, is composed of N-acetyl-2-amino-2-deoxyglucose (GlcNAc) units linked by β-(1 4) bonds (Abdel-Ghany and Salem, 2020, Jiménez-Gómez and Cecilia, 2020). Classified as non-digestible fiber due to the absence of chitinolytic enzymes in most organisms, this biopolymer is the main constituent of insect exoskeletons. The perception that chitin, as non-digestible fibre, negatively impacts the digestibility of lipids and proteins has led to a trend of removing chitin from foods and feeds (Kroeckel et al., 2012). However, recent studies have challenged this perspective, highlighting the potential application of insect flours with chitin and its derivatives as effective prebiotics, antibacterial compounds, and immunomodulators in fish feeds (Ahmed et al., 2021, Dawood et al., 2020, Gaudioso et al., 2021, Rimoldi et al., 2021; Terova et al., 2021).

Other studies have demonstrated that the supplementation of chitin and chitosan in the diet indeed increases growth rates, feed efficiency, and enhances disease resistance in various fish species, including rainbow trout (Oncorhynchus mykiss), Nile tilapia (Oreochromis niloticus), thinlip mullet (Liza ramada), red porgy (Pagrus major), Japanese eel (Anguilla japonica), and yellowtail (Seriola quinqueradiata) (Ahmed et al., 2021, Dawood et al., 2020, Kono et al., 1987, Qin et al., 2014; S. Elserafy et al., 2021; Shi et al., 2020). Similarly, others have shown that certain species such as cod (Gadus morhua) (Danulat, 1986), juvenile cobia (Rachycentron canadum) (Fines and Holt, 2010, channel rockcod (Sebastolobus alascanus), splitnose rockfish (Sebastes diploproa), and black cod (Anoplopoma fimbria) (Gutowska et al., 2004) have been reported to exhibit chitinase activities, that is, enzymes capable of digesting chitin.

However, based on various studies, chitin should not be seen only as a villain. This biopolymer and its derivatives have positive effects on the diversity of the intestinal microbiome, acting as prebiotics and modulating the microbial communities in the fish intestines (Ringø et al., 2006, Terova et al., 2019).

Additionally, they contribute to strengthening the immune system, providing protection against infections (Esteban et al., 2001).

7. PHYSIOLOGICAL RESPONSES OF FISH FEEDING WITH INSECTS

In recent years, several articles and reviews have been published regarding the nutritional value, low environmental impact, and food safety of insects approved by the EU for animal feed (EC Regulation no. 2017/893; European Commission, 2017) (Alfiko et al., 2022). These studies highlight the potential of insects such as HI, TM, and MD as promising alternatives to FM in diets for various freshwater and marine fish species, particularly focusing on Mediterranean aquaculture (Gasco et al., 2016; Henry et al., 2018; Iaconisi et al., 2017; Nogales-Mérida et al., 2019; Piccolo, 2017; Pippinato et al., 2020).

The importance of zootechnical parameters and fish health is highlighted when considering insects as a food source. Studies performed by Chemello et al. (2020), evaluated the complete or partial replacement of FM with TM meal, and the results indicated that both substitutions did not affect rainbow trout growth performance and fillet quality (Belforti et al., 2015, Iaconisi et al., 2018, Rema et al., 2019). Similarly, TM has been successfully used and well-accepted by several marine fish species (Gasco et al., 2016, Iaconisi et al., 2017, Piccolo, 2017).

Research performed on blackspot sea bream (Pagellus bogaraveo) revealed that the inclusion of full-fat T. molitor at 21 % of the feed did not affect fillet EPA or DHA content.

However, when included at 40 %, it decreased the EPA content (Iaconisi et al., 2017). This suggests that dietary insect meal may induce alterations in lipid metabolism, depending on its dietary inclusion level. In a study performed by Mastoraki et al. (2020), replacing fish meal with HIL did not have an impact on the n-3 PUFAs in European seabass when compared with the control diet. In another study, Pulido et al. (2022) observed that in fillets of gilt-head sea bream fed on HIL meals, there was a decrease in n-3 PUFAs in favour of SFAs. The discrepancy in these findings may be related to the nature of HIL meals used, as well as differences in fish species, basal diets, and environmental factors (Mastoraki et al., 2020).

Although several studies have reported the replacement of FM in fish diets using MD larvae, most of them focus on freshwater species such as Nile tilapia (Oreochromis niloticus). However, research has demonstrated that MD larvae can be a viable alternative source for farmed fish, with the potential to economically replace FM, as long as the hydrophobic fraction is removed. The quality of MD larvae, in terms of amino acid profile, is comparable to that of FM, except for taurine, suggesting the need for supplementation for use in aquaculture feed.

Additional studies evaluate the inclusion of insect meal in fish diets, highlighting that growth performance appears to depend on the level of inclusion, fish species, insect species, and nutrient composition (Piccolo, 2017).

In conclusion, the use of insects in aquaculture demonstrates the potential to promote sustainability and productivity, with specific considerations on zootechnical parameters, fish health, and adequate levels of inclusion in the diet.

8. FINAL CONSIDERATIONS

Insects have emerged as one of the most promising substitutes for fishmeal when compared to other new protein sources, such as bacteria, microalgae, macroalgae, and yeasts. Soon, insects may emerge as a viable solution to address the drawbacks associated with FM in the aquaculture industry. The exploration of these alternative protein sources for aquafeeds, particularly through integration of insects, represents a significant stride towards sustainable and eco-friendly aquaculture. HI, TM and MD have emerged as promising candidates for replacing FM in aquafeeds. Insect-based protein sources exhibit diverse benefits, including efficient nutrient utilization, short maturation periods, and cost effectiveness, addressing the economic and environmental challenges associated with conventional aquafeeds products. Over the past decade, numerous studies have investigated replacing FM with insects in aquaculture. All fish trials must follow specific guidelines that address the nutritional needs of each fish species, adapting each formulation accordingly.

Furthermore, it is necessary to evaluate not only the quality of flesh and growth performance but also the microbiome, water impact, and metabolic and physiological responses. This underscores the emerging need for multidisciplinary studies in this field.

Despite the promising results from including insects as ingredients in aquafeed, significant gaps remain regarding their full utilization in aquaculture. Moreover, important bioactive compounds such as chitin, fatty acids, and antimicrobial peptides have been reported in insects; however, their role in aquatic animal growth and physiology is not yet well understood.

Still, the success of this alternative hinges on critical factors, including the specific fish species and incorporation levels. Further exploration is expected to yield recommended guidelines for the incorporation of insect-based products tailored to diverse fish species.

Source : Fantatto, Rafaela R., Mota, J., Ligeiro, C., Vieira, I., Guilgur, L.G., Santos, M., Murta, D., 2024. Exploring sustainable alternatives in aquaculture feeding: The role of insects.
Aquac. Rep. 37, 102228. https://doi.org/10.1016/j.aqrep.2024.102228.

RECENT ADVANCES IN THE UTILIZATION OF INSECTS AS AN INGREDIENT IN AQUAFEEDS

The aquafeed industry continues to expand in response to the rapidly growing aquaculture sector. However, the identification of alternative protein sources in aquatic animal diets to replace conventional sources due to cost and sustainability issues remains a major challenge. Recently, insects have shown tremendous results as potential replacers of fishmeal in aquafeed.

The present study aimed to review the utilization of insects in aquafeeds and their effects on aquatic animals' growth and feed utilization, immune response and disease resistance, and fish flesh quality and safety. While many insect species have been investigated in aquaculture, the black soldier fly (Hermetia illucens), and the mealworm (Tenebrio molitor) are the most studied and most promising insects to replace fishmeal in aquafeed, and their recommended inclusion levels for aquatic animals vary depending on the insect species used, biomass processing method, and test organism.

But, more studies are needed to establish optimum requirements levels for different aquaculture species at different stages of development and under different culture systems.

1. INTRODUCTION

The global population is expected to reach nearly 10 billion people by 2050 (United Nations, 2019). Therefore, the food production sector, particularly animal protein production will play a critical role in food and nutrition security. In most global communities, fish is the cheapest and most readily available source of animal protein (Maulu et al., 2020).

Aquaculture is not only the fastest-growing food production sector but also a major contributor to global food fish (Food and Agriculture Organization [FAO], 2020). Besides, aquaculture is the most sustainable and efficient way of producing aquatic products (FAO, 2020; Maulu et al., 2021a).

However, the increasing costs of production in aquaculture due to the rising cost of feeding threaten the sustainability of the sector (Dawood, 2021). This is primarily caused by the overdependence of intensive aquaculture production on fishmeal and fish oils as major feed ingredients whose prices continue to rise due to declining production (Dawood, 2022; Hazreen-Nita et al., 2022). In addition, the food-feed-fuel competition for the limited resources under the current changing climatic conditions has drastically affected the availability of conventional feedstuffs such as fishmeal, soybean and cereals, leading to a decline in availability and high volatility in feed ingredient prices (Mugwanya et al., 2022).

Besides, plant-based ingredients have been reported to cause negative side effects in the gut of carnivorous fish due to the presence of anti-nutritional factors (Zhou et al., 2018) and complex indigestible carbohydrates (Gaudioso et al., 2021), consequently impacting growth and welfare of the fish. Therefore, recent studies have focused on evaluating potentially sustainable alternatives including insects (Li et al., 2019; Alves et al., 2021; Terova et al., 2021), bacteria (Maulu et al., 2021b; Li et al., 2021) and organic by-products (Mo et al., 2014; Cheng et al., 2017). Among these, insects have attracted the most attention due to their wide application in aquaculture and ease of production.

Insects are reported to contain high crude protein content of 34% to 74% dry matter, DM (Freccia et al., 2020; Gasco et al., 2020). However, most whole-insects contain 42% to 63.3% crude protein on a dry matter basis (Alfiko et al., 2022) with up to 74% reported when insect meal is defatted (Alfiko et al., 2022). Additional nutritional value includes a well-balanced essential amino acid (EAA) profile resembling that of fishmeal, high lipid (10% to 30%), DM level (albeit high variability in fatty acid profiles), a good source of vitamins like vitamin B12, and some bio-available minerals like iron and zinc (Alegbeleye et al., 2012; Gasco et al., 2020). Furthermore, insect meal contains bioactive compounds (e.g., chitin, fatty acids and antimicrobial peptides) with prebiotic, antioxidant and antimicrobial properties that promote animal health and counteract antimicrobial resistance (Gasco et al., 2018; Veldkamp et al., 2022).

However, the nutritional composition varies with insect species (DeFoliart, 1995; Barroso et al., 2014), the rearing process (Zarantoniello et al., 2020) and the production process of the protein (Ramos-Elorduy et al., 2002), suggesting that the proximate composition could be modified to suit specific requirements. For instance, defatting increases the protein content in insect meal (Alfiko et al., 2022), while rearing the insects on substrate rich in n-3 polyunsaturated fatty acids (PUFAs) could increase the PUFA profile content in insects (Zarantoniello et al., 2020). Unlike fishmeal and plant-based protein, insects can be produced intensively within a short time with little need for arable land, reduced water consumption/utilization, lower greenhouse gas (GHG) emissions, and bio-waste conversion (Gasco et al., 2020; Pulido-Rodriguez et al., 2021). Thus, insect farming is considered sustainable due to its low ecological footprint. Also, when used in diets with multiple ingredients including plant-based proteins, insects have shown potential to counteract the negative effects on growth and gut health in carnivorous species, which are usually common when fishmeal is replaced with plant protein (Randazzo et al., 2021; Pulido-Rodriguez et al., 2021; Gaudioso et al., 2021).

The unique properties of insects and their suitability for application in aquafeeds as fishmeal and fish oil replacement have become a hotspot for research in aquaculture. Numerous authors have reviewed the existing literature to identify findings that provide a map for future development.

Most of these studies have focused on the nutritional composition of different insects used in aquafeeds, their production technology, and prospects (Henry et al., 2015; Nogales-Mérida et al., 2018; Ameixa et al., 2020; Gasco et al., 2020; Oonincx and Finke, 2021; Alfiko et al., 2022).

Others have further highlighted the effect of insects in aquafeed on aquatic animals (Wang and Shelomi, 2017; Freccia et al., 2020; Hawkey et al., 2021). English et al. (2021) reviewed the advancements in the production methods for BSF and their application in salmonids, while Priyadarshana et al. (2021) reviewed the application of BSF meal focussing on growth performance and body composition in finfish. Mousavi et al. (2020) reviewed the functional properties of insects focussing on their immunomodulatory and physiological effects on aquatic animals.

Other reviews, such as those of Zarantoniello et al. (2020) and Shafique et al. (2021) only focused on a single insect species and its effect on fish. Hodar et al. (2020) broadly looked at a range of alternative protein alternatives (including insects) as potential fishmeal and fish oil replacement in aquafeeds while Liland et al. (2021) performed a meta-analysis on the nutritional value of insects in aquafeeds. More recently, Alfiko et al. (2022) reviewed the status and trends in the application of insects in fish feeds.

In this study, we provide a more comprehensive overview of the most recent advances in the utilization of insects as a promising aquafeed ingredient.

This paper attempts to bridge the gap in the existing literature by presenting information on the response of different aquaculture species to insect-based feeds and opportunities for further improvement.

2. INSECT SPECIES UTILIZED IN AQUAFEED

Nowadays, insects are viewed as the most promising and sustainable source of animal protein mainly because of their nutritional value, amino acid composition and ease of propagation (Iaconisi et al., 2019; Gasco et al., 2016, 2020; Biancarosa et al., 2019; Tilami et al., 2020; Were et al., 2021). Many of these insects have shown beneficial conversion factors and productivity, fast life cycles and the ability to grow on a variety of available substrates, yielding high quality and readily assimilated proteins and highly unsaturated fatty acids (HUFA), as well as vitamins and functional compounds (Tacon and Metian, 2008; Gasco et al., 2016; Turek et al., 2020; Shafique et al., 2021).

Consequently, some have been incorporated into aquafeed formulations for different aquatic species, yielding interesting results. The most promising insect species whose meal has been used to replace fish meal and/or fish oils include the black soldier fly (BSF, Hermetia illucens), the yellow mealworm (TM, Tenebrio molitor) and the common housefly (MD, Musca domestica) (Belforti et al., 2015; Gasco et al., 2020; Iaconisi et al., 2019; Sogari et al., 2019). So far, BSF, TM and MD have well-documented production processes.

Although some of the insects like the house fly are known to be parasitic and disease vectors, other species like the BSF are considered symbiotic (Menino and Murta, 2021) as they can be propagated without causing any known harm to humans.

Unlike animals, the feed conversion rate and GHG emissions of insects are much lower in a certain temperature range since insects do not use energy to maintain their body temperature in a strict range (Belforti et al., 2015).

Irrespective of the different methods of propagation and production of different species, insects have shown promising results for potential use as a protein and oil source in aquafeed.

Many studies have revealed that insect meals and oil can partially or completely replace the fish and soybean meals and oils that are commonly used in aquaculture production (Henry et al., 2015; Nogales-Mérida et al., 2018; Fawole et al., 2020; Tilami et al., 2020; Xu et al., 2020a; Hender et al., 2021). Insects such as the BSF have been extensively studied, not only in fish culture but also in poultry and swine (Sogari et al., 2019).

In aquaculture, many studies have revealed positive results when BSF meal was used as a substitute for fish meal for many species such as whiteleg shrimp (Litopenaeus vannamei) (Richardson et al., 2021), barramundi (Lates calcarifer) (Hender et al., 2021), climbing perch (Anabas testudineus) (Mapanao et al., 2021), Nile tilapia (Oreochromis niloticus) (Were et al., 2021), African catfish (Clarias gariepinus) (Fawole et al., 2020), Japanese sea bass (Lateolabrax japonicus) (Wang et al., 2019), Atlantic salmon (Salmo salar) (Lock et al., 2016; Stenberg et al., 2019), Siberian sturgeon (Acipenser baerii) (Zarantoniello et al., 2021), gilthead sea bream (Sparus aurata) (Randazzo et al., 2021), clownfish (Amphiprion ocellaris) (Vargas-Abúndez et al., 2019) and in rainbow trout (Oncorhynchus mykiss) (Cardinaletti et al., 2019) to produce food fish.

In the aforementioned species, BSF improved various growth parameters as well as the immune response to some diseases affecting aquatic species. Also, TM has shown positive results when utilized in the diets of many aquatic species, such as yellow catfish (Su et al., 2017), gilthead seabream (Fabrikov et al., 2021), largemouth bass (Micropterus salmoides) (Su et al., 2022), seabass (Dicentrarchuss labrax) (Reyes et al., 2020), narrow-clawed crayfish (Pontastacus leptodactylus) (Mazlum et al., 2021), olive flounder (Paralichthys olivaceus) (Jeong et al., 2021), black porgy (Acanthopagrus schlegelii) (Jeong et al., 2022) and rainbow trout (Su et al., 2017; Melenchón et al., 2021).

Furthermore, TM has a relatively high nutritional value as well as being a rich source of essential amino acids (methionine), lipids and fatty acids, that vary based on the developmental stage of the larvae (Shafique et al., 2021).
Despite limited information existing, the nutritional properties of insects for use in aquafeed are likely to vary across and within aquaculture species depending on developmental stage, culture media and rearing conditions (Liu et al., 2017; Yu et al., 2021). Overall, the proximate composition of most insects decreases with advancement in the developmental stage.

3. INSECT BIOMASS PRODUCTION AND PROCESSING FOR AQUAFEED

The conversion of insects into aquafeed ingredients is an important step that determines their required level and effectiveness in aquatic animals. With the discovery of insects and their potential for replacing fishmeal in animal feeds, there is a danger that natural harvests could have serious biodiversity conservation-related issues. Hence, the mass production of insects for commercial-scale industry from agricultural organic residues and biowaste for feed purposes or food is a promising and sustainable approach (Varelas, 2019).

However, due to variations that occur during culturing under controlled environments for insect mass production, the nutritional value is also expected to vary (Varelas, 2019). For example, Cortes Ortiz et al. (2016) noted that the artificial diets required by insects differ not only in presentation, from liquid to solid, but also in nutritive value, the feeding adaptation of the insect, insect species and the pre-manufacture method.

Additionally, insects have been reported to have variable fatty acid profiles, particularly having a low level of PUFAs. PUFAs have important health benefits in humans and are required for optimal growth and development in children (Maulu et al., 2021c).

Therefore, it is important to incorporate PUFA enrichment methods such as rearing insects in n-3 PUFA-rich substrates as demonstrated by Zarantoniello et al. (2020). Erbland et al. (2020) reported that insects can accumulate eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) by modifying their rearing substrates.

The authors supplemented a chicken feed diet with increasing concentrations of salmon oil (0% to 42%) to the substrate over an increasing number of days (0 to 8 d) to improve the concentration of omega-3 fatty acids in BSF larvae.

The accumulation of EPA and DHA was achieved in BSF and TM larvae by feeding the insects with round sardinella (Sardinella aurita Valenciennes, 1847) and blackspot seabream (Pagellus bogaraveo, Brünnich, 1768) discards.

Similar findings were reported by Romero-Lorente et al. (2022) in TM larvae, however, the authors suggested that longer pre-treatment, for 5 days, would be required.

Tirtawijaya and Choi (2021) fortified BSF larvae substrate with squid liver at different concentrations of 2.5% to 20% and a concentration of 5% was reportedly required to achieve a better accumulation of EPA and DHA in the insect. Very long-chain polyunsaturated fatty acids (VLCPUFAs) could be altered in BSF larvae by modifying the diet of the insect (Barroso et al., 2017). Overall, these studies indicated the possibility of improving the nutritional value of insects for use in aquafeed by modifying their rearing conditions. However, the fatty acid composition of the substrate and the weight of the insect larvae are determinants of the fatty acid profile (Ewald et al., 2020).
In a review by Varelas (2019), the different methods of insect biomass production from food waste are presented in more detail. For insects to remain a sustainable protein source in aquafeed, low-cost production technology for commercial industries is very crucial. Thus, various biomass processing methods have recently been reviewed. The most recent one is that of Parniakov et al. (2021) where a comprehensive overview of insect biomass processing methods is discussed.
So far, several parts of insects, including meal (Ido et al., 2019), the pulp (Xu et al., 2020b), paste (Weththasinghe et al., 2021), frass (Yildirim-Aksoy et al., 2020) and oil (Kumar et al., 2021) have been used as ingredients in aquafeed. However, the meal, either full-fat or defatted is the most commonly used form of insects in aquafeed.

For example, the BSF is processed mainly into a dry meal using partially defatted or full-fat larvae (English et al., 2021). In yellowtail (Seriola quinqueradiata), feeding the fish with completely defatted BSF larvae meal enhanced the growth of the fish compared with using partially defatted larvae (Ido et al., 2021). Therefore, defatting insects before milling for inclusion in aquafeed could yield better results in many fish species. For commercial use, BSF is processed using technologies like drying ovens (Dortmans et al., 2017) while defatting is achieved using an oil press or centrifuge (English et al., 2021). Drying at the right temperature is important particularly for storage purposes as it prevents microbial activity from affecting the nutritional value of the product (Dortmans et al., 2017). Defatting is recommended because it renders a product with high protein content and low moisture which is ideal for feeding and storage (Dortmans et al., 2017). As BSF larvae are usually dried at high temperatures (>90 °C), there are concerns that there will be a decrease in the nutrient (protein) digestibility coefficient which could negatively affect fish growth (Weththasinghe et al., 2021; Xu et al., 2020a). However, few studies have comprehensively investigated the effect of processing such as drying temperature and pressure of partially defatted, fully defatted, or full-fat BSF larvae meals in diets for fish (English et al., 2021).

Therefore, further research is needed in that regard. Most studies simply investigate the effect of one processing method e.g., partial defatting in comparison to the fishmeal control diet, although they try to regulate temperature below 90 °C when drying the larvae.

The TM larvae can be fed fresh (Henry et al., 2015) or prepared as a meal by oven drying, sun drying or freeze-drying the larvae before grinding. As with BSF, processing of TM by defatting or utilizing it with full fat could affect acceptability and consequently maximum inclusion levels in diets (Shafique et al., 2021). However, defatted TM has been reported to provide the benefit of increased protein content and a more stable pelleting process of the feed (Shafique et al., 2021).

Other insects such as the MD and earthworm (Perionyx excavates) could be processed by boiling in hot water followed by drying in an oven before being milled (Gbai et al., 2018). Interestingly, the mopane worm (Imbrasia belina) has been processed by first gutting it before boiling in brine and later sun-drying in preparation for grinding into a meal (Rapatsa and Moyo, 2017).

Although degutting is mainly used for preservation purposes, the authors observed that the plant matter in the gut of the mopane worm could contain amylase activity. Further studies are necessary to investigate the effect of degutting the mopane worm before use in aquafeed.

4. UTILIZATION IN AQUAFEEDS

4.1. RECOMMENDED LEVELS IN DIETS FOR AQUATIC ANIMALS

The incorporation of insects in aquafeed has been investigated and is considered a breakthrough in the efforts to replace fishmeal in many aquaculture species. Currently, a very limited number of studies have determined the optimal requirement levels of insect meals in aquafeed (Katya et al., 2017; Shekarabi et al., 2021; Tippayadara et al., 2021). What is available are mostly recommended levels based on the results yielded from insect meal inclusion in the diets mainly as replacements for fishmeal. The results reported so far regarding insect incorporation levels in aquafeeds have shown conflicting results depending on factors such as fish species, growth stage, feed formulation, insect biomass processing method and dietary administration period. A recent review of the meta-analysis studies on the nutritional value of insects in aquafeed indicates a high degree of variation regarding the maximum inclusion levels of insects in aquafeed based on these factors (Liland et al., 2021). Hence, the authors observed that 20% to 30% could be the maximum range for insect meal inclusion levels without adverse effects. Also, whether the diet is plant-based or animal-based appears to influence the insect requirement level of different species. Earlier reviews predominantly focused on inclusion levels of insect meals in freshwater species (Henry et al., 2015) but recent reviews are broadening the scope to include marine species (English et al., 2021; Priyadarshana et al., 2021). This is because of the growing evidence that insect meal requirement levels between freshwater and marine aquaculture species could vary. However, there are no studies that have critically compared this in aquatic animals even though it is obvious that the nutritional requirements between the two are different. In some marine fish species, such as the European seabass (D. labrax), optimal growth had previously not been achieved by replacing fishmeal with full-fat insect meal at levels higher than 50% (Basto et al., 2021). This was attributed to n-3 long-chain polyunsaturated fatty acids (LC-PUFA) deficiencies (<0.7% DM) at higher fishmeal replacement levels (Skalli and Robin, 2004).

A recent study by Basto et al. (2021), however, showed that up to 80% (360 g/kg) of fishmeal could be replaced by TM in the diet of D. labrax fingerlings without detrimental effects on growth and nutrient digestibility. As aquaculture is a diverse industry in terms of cultured species and their developmental stages, production systems used and culture conditions, more studies are required to investigate insect meal requirement levels in aquatic animals. Most of the progress made in the utilization of insects in aquafeed has focused on replacing fishmeal due to rising costs and sustainability issues. As such, most of the existing studies have investigated the effect of replacing fishmeal at different levels in the diets of aquatic animals with a view to partially or fully replace fishmeal. This has been done either by combining some insect species (Hoffmann et al., 2021) or singly, with amino acids supplemented to meet the EAA requirements of fish (Chemello et al., 2020). However, when used in combination, Hoffmann et al. (2021) reported that the type of insect meal had a crucial impact on fish growth and feed utilization parameters. In their study, the authors noted that combinations of full-fat larval stage TM and BSF meal performed better than combinations of imago stage tropical house cricket (Gryllodes sigillatus) and Turkestan cockroach (Blatta lateralis) in diets of sea trout (Salmo trutta) larvae. In Eurasian perch (Perca fluviatilis), fingerlings fed an experimental diet containing a combination of 50 g/kg house cricket and 50 g/kg of superworm (25% fishmeal replacement) had significantly lower growth compared to the control (Tilami et al., 2020). This was attributed to several factors including reduced feed intake (palatability), presence of chitin and oxidized fat. Insects have also been used singly or in combination with other ingredients to replace plant-based proteins in animal diets. For instance, BSF inclusion at 324 g/kg (47% replacement of vegetable mix) and BSF and protein by-product meal (PBM) inclusion levels at 81 and 206 g/kg, respectively (49% replacement of vegetable mix), led to faster growth of gilthead seabream in comparison to the vegetable mix and fishmeal only controls (Randazzo et al., 2021).

This study is of interest because while it is important to look at studies in which insect meals are used to replace fishmeal in aquafeeds; it is also beneficial to compare the effects with insect replacement in commonly utilized plant-based diets.

The presence of chitin in insect meals could have beneficial effects on fish by shaping the gut microbial community and boosting the innate immune response when incorporated at moderate quantities ranging from 25 to 50 mg/kg (Esteban et al., 2001; Bruni et al., 2018). On the other hand, the effect of higher inclusion levels of insect meal has been reported to yield negative results in most species, and this has been associated with the increased level of chitin at higher levels (Kroeckel et al., 2012; Renna et al., 2017). For instance, BSF larvae meal incorporated at 400 g/kg (corresponding to a chitin level of 2 g/100 g DM) was reported to reduce dry matter and crude protein digestibility but did not affect growth in rainbow trout (O. mykiss) (Renna et al., 2017). BSF pre-pupae meal incorporated in diets of juvenile turbot (Psetta maxima) at levels higher than 332 g/kg (chitin level ranging from 47 to 73 g/kg DM) led to reduced feed intake and feed conversion and subsequently reduced growth (Kroeckel et al., 2017). According to Soetemans et al. (2020), the crystalline nature of chitin present in some insects is what limits its utilization in aquafeed. Wang et al. (2020) found that this crystalline nature increases with the advance in developmental state of insects, particularly BSF from larvae to adults. For example, in Siberian sturgeon juveniles, the inclusion of highly defatted BSF meal from 185 to 375 g/kg (25% to 50% fishmeal replacement; 0.72 to 1.92 g/100 g chitin in feed) reduced the feed intake and apparent digestibility coefficient (ADC) of protein, while inclusion at 750 g/kg (100% fishmeal replacement; 3.75 g/100 g chitin in feed) led to complete rejection of the feed (Caimi et al., 2020a). Feeding sea trout (S. trutta) fingerlings with hydrolyzed TM at an inclusion level of at least 100 g/kg (9.3 g/kg chitin in feed; 42% fishmeal replacement) resulted in a significantly reduced protein efficiency ratio (Mikołajczak et al., 2020). However, whether insect biomass processing methods affect the chitin content in the meal is not yet clear and as such, further studies are required.

Although Gasco et al. (2018) reported that the content level of chitin can be reduced through the extraction process or dietary enzyme inclusion to improve its digestibility; appropriate technologies have not yet been fully applied. Jayanegara et al. (2017) were able to completely remove chitin from cricket (Gryllus assimilis) by chemical digestion while reducing chitin levels from 7.7% dry matter to 3.5% by exoskeleton removal.

Besides the presence of chitin, negative effects observed in aquatic animals when insect meals are incorporated in aquafeeds can be attributed to lower levels of fatty acids in the diets in comparison to the fishmeal control diet (Zarantoniello et al., 2021). Insects have been reported to have lower levels of n-3 PUFA (Zarantoniello et al., 2020) and therefore without sufficient enrichment processes in the insect rearing process, this might translate to lower n-3 PUFA levels in the aquafeeds. For instance, in a study by Zarantoniello et al. (2021), diets in which 50% fishmeal was replaced by BSF had significantly lower n-3 fatty acids. Consequently, Siberian sturgeon fed these diets had significantly lower growth and specific growth rate than those fed the control diet. According to the authors, the fish spent energy converting linoleic acid and α-linolenic acid to EPA and DHA instead of utilizing the energy all for growth.

Additionally, the authors reported lower diet acceptance in the fish-fed diets containing 50% insect meal thus, requirement levels might be affected by the palatability of the diets (Zarantoniello et al., 2021). However, several studies have shown that the absence of LCPUFA in terrestrial insects can be alleviated by feeding insects with diets rich in n-3 LCPUFA (Barroso et al., 2017; Fabrikov et al., 2020, 2021; Tirtawijaya and Choi, 2021).

In other studies, the negative effects when aquatic animals are fed with higher dietary levels of insect meal were attributed to the presence of non-protein nitrogen in some insects, which could lead to the overestimation of protein (Janssen et al., 2017).

4.2. EFFECTS OF INSECT MEAL ON AQUATIC ANIMALS

4.2.1. GROWTH AND FEED UTILIZATION

The growth performance and feed utilization effects of several insects have been studied in aquaculture. These include BSF (Fawole et al., 2020; Peng et al., 2021b), yellow mealworm (T. molitor) (Sankian et al., 2018), housefly (M. domestica) (Hashizume et al., 2019), mopane worm (I. belina) (Rapatsa and Moyo, 2017), chironomid (Roncarati et al., 2019) and cricket (G. bismasculatus) (Taufek et al., 2016), with BSF being the most studied insect in aquaculture. Insects can be utilized either as dry meals (Jeong et al., 2021; Kamarudin et al., 2021), pulps (Peng et al., 2021a, 2021b), or oils (Belghit et al., 2018; Xu et al., 2020a; Abu Bakar et al., 2021). For example, Fawole et al. (2020) carried out a 60-day experiment to examine the effect of fish meal substitution with BSF larvae meal at 25%, 50% and 75% on the growth performance, nutrient utilization and health parameters of African catfish (C. gariepinus). This study discovered that black soldier fly larvae meal at 50% presented the highest final body weight, weight gain and specific growth rate compared to other groups. Feed conversion ratio, protein efficiency ratio and protein productive value were better in fish fed 50% BSF larvae meal (Fawole et al., 2020). According to Kamarudin et al. (2021), a black soldier pre-pupae meal inclusion level of 75% was needed to increase the growth performance of lemon fin barb hybrid fingerlings. A study by Belghit et al. (2019) indicated that a total replacement of fish meal with BSF meal was possible in Atlantic salmon (S. salar) without compromising their growth and nutrient digestibility. Furthermore, the dietary inclusion of black soldier fly pulp reportedly improved the growth performance of largemouth bass (M. salmoides) (Peng et al., 2021a, 2021b). Xu et al. (2020a) compared the dietary effect of BSF, TM and silkworm oils on the growth and other metabolic parameters of the juvenile mirror carp (Cyprinus carpio).
The results showed that BSF oil alone or in combination with two of the other insect oils in fish diets significantly enhanced the growth and feed utilization of the fish.

TM is the second most widely studied insect in aquaculture after BSF, with the potential to be utilized as an optional protein ingredient in aquafeed.

A study by Rema et al. (2019) reported that graded inclusion of defatted TM increased the growth and feed utilization of rainbow trout (O. mykiss) and showed the potential to completely replace fish meal. Improved growth and feed utilization parameters were also reported in freshwater prawns (Macrobrachium rosenbergii) (Feng et al., 2019) and mandarin (Siniperca scherzeri) (Sankian et al., 2018) fed TM diets. On the contrary, no significant effect on the growth and feed utilization parameters was observed when mealworm was used to partially substitute fish meal at 25% and 50% for 131 days in blackspot seabream (P. bogaraveo) (Iaconisi et al., 2017). The same was reported in O. mykiss (Iaconisi et al., 2018) and yellow catfish (Pelteobagrus fulvidraco) (Su et al., 2017). However, negative effects on growth performance and feed utilization of TM were reported in some fish species (Coutinho et al., 2021; Jeong et al., 2021). These findings may call for better processing of the ingredient and the need for further studies to optimize this ingredient in aquaculture.

Furthermore, the housefly (M. domestica) (Hashizume et al., 2019), mopane worm (I. belina) (Rapatsa and Moyo, 2017), chironomid (Roncarati et al., 2019) and cricket (G. bismasculatus) (Taufek et al., 2016) are some of the insects that showed potential to be used as protein ingredients to improve fish growth, however, more research is deemed important.

4.2.2. ANTIOXIDANT CAPACITY

The effect of insect utilization in aquafeed on the antioxidant capacity of fish has been reported in numerous studies with promising results. However, the results vary depending on the insect species and parts used in aquafeed.

For example, dietary insect (such as BSF) meal as a replacement for fishmeal showed deleterious effects on the transcription of antioxidant enzymes and stress-related genes in the leukocytes of the head kidney (Stenberg et al., 2019). In the African catfish, substituting fishmeal with BSF at 75% did not impair the antioxidant status of the fish (Fawole et al., 2020). In rainbow trout, Elia et al. (2018), reported that dietary inclusion of at least 20% BSF could adversely affect the fish's oxidative homeostasis, particularly in the liver and kidney by lowering the glutathione peroxidase (GPx) activity while enhancing the activities of ethoxyresorufin O-deethylase (EROD), glutathione S-transferase (GST) and total glutathione (GSH).

Therefore, the authors suggested adding levels of BSF that are lower than 20% in the fish's diets. In Atlantic salmon, increasing the levels of BSF paste from 6.25% to 25% in fishmeal and plant-based diets improved the antioxidant capacity in the blood of the fish (Weththasinghe et al., 2021). In Pacific white shrimp, dietary replacement of fishmeal with defatted silkworm (SW) (B. mori L.) pupae meal enhanced the serum antioxidant capacity of the shrimp (Rahimnejad et al., 2019). Recently, Xu et al. (2020a) reported the effect of insect oils on the antioxidant status of juvenile mirror carp (C. carpio var. specularis). In this study, the combined inclusion of BSF oil, silkworm pupae oil and TM oil at the same level improved the antioxidant capacity in the liver of the fish.

When individual insect oils were compared, the authors observed that BSF oil could provide better results compared to the other two oils.

Furthermore, Xu et al. (2020b) reported significantly improved serum antioxidant capacity in mirror carp fed dietary BSF pulp at low levels. Other insect meal proteins that have shown similar results include cricket (Gryllus bimaculatus) meal in the diet of African catfish (Taufek et al., 2016) and maggot meal in the diet of common carp (Ogunji et al., 2011).

Dietary inclusion of TM in the diet of rainbow trout improved the intestinal antioxidant enzyme activity and a led to a decline in lipid peroxidation (Henry et al., 2018). The antioxidant capacity of the hybrid tilapia was not affected when the fish was fed a diet containing maggot meal as a full replacement for fishmeal (Qiao et al., 2019).

4.2.3. IMMUNE RESPONSE AND DISEASE RESISTANCE

The response of immune function in aquatic animals to dietary supplementation has become an important criterion for evaluating the suitability of feed ingredients in aquaculture.

Insect utilization in aquafeed has been evaluated on several immune-related parameters including blood biochemical composition, histopathology of related organs, gut health, related gene expression and disease resistance in numerous aquaculture species.

The utilization of insect meals in aquaculture could promote the use of plant-based protein, particularly soybean meal whose application in the culture of high-value species has declined because it causes intestinal enteritis. In rainbow trout, the inclusion of BSF meal in soybean meal-based diets successfully prevented soybean meal-induced intestinal enteritis (Kumar et al., 2021). This was accompanied by down-regulated prostaglandin and interferon regulatory factor 1 (IRF-1) in the fish's intestine.

However, the mechanism through which insect meal prevents soybean meal-induced enteritis in fish is not clearly understood. According to Xiang et al. (2020), insect meal contains bioactive peptides that could be attributed to the prevention of this disease. Therefore, insect meal presents the potential prevention of intestinal inflammation in aquaculture. However, as observed by Kumar et al. (2021), this requires further investigation to characterize the bioactive peptides present in insect meals.

In some aquaculture species, the component of the insect used in the diet could yield different results. Furthermore, different organs of aquatic animals could respond differently to varying levels of insect meal included in the diets.

For example, in the diets of Atlantic salmon, the inclusion of 6.25% and 12.5% of BSF meal in fishmeal and plant-based diets could reduce the enterocyte steatosis in the pyloric caeca of the fish (Weththasinghe et al., 2021). On the contrary, 3.7% and 6.7% of BSF paste would be required to yield similar results (Weththasinghe et al., 2021). The authors further observed that increasing the inclusion levels to 25% (BSF meal) and 6.7% (BSF paste) improved the histology of the distal intestine. A minor effect of BSF meal and BSF paste on the skin mucus proteome and immune response in Atlantic salmon has also been reported (Weththasinghe et al., 2021). In the hybrid tilapia (Nile × Mozambique, O. niloticus × O. mossambicus), Yildirim-Aksoy et al. (2020) used frass, a by-product of BSF fly larvae, as a protein source to replace plant-based protein in the diet. The authors reported improved innate immune response and disease resistance against bacterial (Flavobacterium columnare and Streptococcus iniae) infection. Some studies have also reported the effect of BSF oil in aquatic animals and studies in this area are likely to increase as aquaculture moves towards sustainability. In rainbow trout, BSF oil showed beneficial effects on the immunity of the fish in the liver, intestine and kidney (Kumar et al., 2021). In the findings of Dumas et al. (2018), the inclusion of BSF oil in the diet of rainbow trout did not affect the histology of the posterior intestine, although the villus height in the anterior intestine was reduced. In juvenile mirror carp, Xu et al. (2020b) reported that dietary inclusion of BSF pulp at low levels (less than 131 g/kg) did not significantly affect the health status of the intestine.

4.2.4. EFFECT OF INSECT MEAL ON FISH FLESH QUALITY AND SAFETY

Fish flesh quality and safety are of primary importance for consumers and thus those parameters should be evaluated in fish fed insect-derived products. The fatty acid profile of fish flesh is of utmost importance for human health, particularly the n-3 PUFA; EPA and DHA. The fatty acid profile of insect-derived products varies greatly with insect species, production system and product processing method (Gasco et al., 2018, 2019a; Oonincx and Finke, 2021). Generally, insect meals are deficient in EPA and DHA and rich in saturated fatty acids (SFA); a limitation that compromises the n-3/n-6 ratio when insect products are included at increasing levels in fish diets (Belforti et al., 2015; Iaconisi et al., 2017, 2018; Gasco et al., 2019b). Fatty acid profiles in fish-fed insect-derived products are not quite consistent and the general trend regarding EPA and DHA (and other fatty acid missing in insects) in trials with insect-based diets show a decrease of these fatty acids when they are not supplemented otherwise. Feeding high levels of BSF larvae meal to rainbow trout (40% inclusion level; Renna et al., 2017; Mancini et al., 2018; Secci et al., 2019) or Jian carp (14% inclusion level; Zhou et al., 2018) has been shown to decrease both n-3 and n-6 PUFA but increase the SFA content. Similar findings were observed in rainbow trout (O. mykiss) fed live adult house cricket Acheta domestica or live superworm Z. morio larva (at 25% and 100% of gross energy, single or in combination); EPA and DHA content in muscle of fish fed insects was 45% and 63% of the control fish, respectively (Turek et al., 2020). Similarly, there was a reduction in the n-3/n-6 ratio and the relative content of EPA and DHA (% total fatty acids) in the muscle of European seabass fed defatted TM larvae meal that replaced fish meal at increasing levels (0%, 50%, and 100%), however, the absolute value of EPA + DHA in a fillet portion of 100 g for human consumption remained above the recommended level for human consumption (>0.25 g/100 g of wet weight) in all fish and did not vary significantly among treatments (Sousa, 2020). In contrast, the n-3/n-6 ratio and the EPA and DHA content were increased in sea-water Atlantic salmon fed diets in which BSF larvae meal completely substituted fish meal (Belghit et al., 2019). Overall, 10% of HM, corresponding to 17% of FM replacement, might be included in meagre diets without major adverse effects on growth, feed utilization, whole-body composition and fatty acid profile.

Furthermore, despite high dietary inclusion of BSF larvae (H. illucens) meal (0%, 9.2%, 18.4% and 27.6%, corresponding to 0%, 25%, 50% and 75% of fishmeal substitution) reduced the n-3 PUFA in gilthead sea bream fillets, it did not reduce the overall n-3 PUFA positioned in the sn-2 of fillet triglycerides, nor EPA percentage (Pulido et al., 2022). Replacement of 25% fishmeal by a mixture of house cricket (Acheta domesticus) and superworm (Z. morio) in the diet of perch (Perca fluvatilis) increased the linoleic fatty acid and the total content of n-6 fatty acids in fish fillets but did not affect the nutritional value of the fish with the insect-based diet for human consumption, despite a decrease in growth performance and an increase in feed intake (Tilami et al., 2020). The effects of insect-derived product feeding on the content of heavy metals and mycotoxins in fish flesh are rarely investigated and warrant further work.

Regarding fish texture properties, fishmeal replacement using insect meals might have an impact.

Texture parameters are technologically important (Wang et al., 2017) therefore, need not be overlooked. Incorporation of maggot meal in diets of Nile tilapia (O. niloticus) at levels ranging from 110 g/kg to 430 g/kg (25% to 100% fishmeal replacement) significantly increased hardness and reduced thaw loss in comparison to the control (Wang et al., 2017). Incorporation of TM in diets of yellow croaker (Larimichthys crocea) led to increased muscle hardness and significantly lower shear force in fillets in which fishmeal was replaced at 426.2 to 568.3 g/kg (75% to 100% fishmeal replacement) (Yuan et al., 2022). Fillet composition was not affected by the inclusion of BSF (H. illucens) pre-pupae larvae meal at 65 to 195 g/kg (15% to 45% fishmeal replacement) in diets for European seabass (D. labrax) (Moutinho et al., 2021). There were no significant differences in texture properties of fillets of barramundi (L. calcarifer) fed diets supplemented with tuna hydrolysate and BSF (H. illucens) larvae meal (50 to 100 g/kg insect meal inclusion levels) (Chaklader et al., 2021).

4.2.5. CONSUMER OPINION ON THE CONSUMPTION OF AQUACULTURE PRODUCTS FED WITH INSECT MEAL

The use of insects as feed ingredients in aquaculture is a relatively new but highly promising technology for mitigating the rising cost of aquafeed due to sustainability issues of fishmeal (Baldi et al., 2021; Hasimuna et al., 2019; Kord et al., 2022). However, the wider adoption of insect utilization in aquafeed will likely depend, to a larger extent, on aquaculture producers and consumer acceptance. Despite few existing studies investigating people's perception concerning the use of insects as feed ingredients, the majority of the aquatic animal product consumers have shown favourable responses for various reasons, including risk-free (Popoff et al., 2017; Szendrő et al., 2020), sustainability considerations (Verbeke et al., 2015; Rumbos et al., 2021), as well as availability and access to information about the products (Baldi et al., 2021; Rumbos et al., 2021).

Product awareness and information availability are considered the most important factors that could accelerate the acceptance and positive perception of aquatic products produced on insects-based feeds (Baldi et al., 2021; Rumbos et al., 2021). According to Baldi et al. (2021) reducing information asymmetry could promote wider consumer acceptance. Interestingly, a study conducted in Italy revealed that men and young consumers are more likely to accept aquatic products given insect-based feeds (Baldi et al., 2021), suggesting that gender and age could play a role. Further, the authors observed that well-informed respondents had a higher acceptance rate compared with those that had little to no information. Sogari et al. (2019) also noted that, in Australia, males were more likely to accept insect products as food compared with their female counterparts.

However, in Belgium, age and gender did not appear to significantly affect the perception of the aquatic products. As observed by Verbeke (2015), consumer perception regarding insect use in aquafeed is likely to evolve with time and vary based on culture, familiarity and past experiences, meaning that acceptance of aquatic products fed insect-based diets will improve with accumulation of information about the product.

Additionally, different cultures and beliefs are likely to affect perception although further studies are required to confirm it. Currently, the majority of existing studies were conducted in developed countries, particularly the European Union (EU), with no current information for developing countries.

5. CONCLUSION

Insects have emerged as a potentially sustainable alternative protein source to the conventional fishmeal whose production continues to be unsustainable, resulting in rising costs. Significant progress has so far been made in the efforts to unlock the potential of insects for use in aquafeed.

Our review of existing studies in this area has shown promising results, particularly with regards to enhanced growth performance, nutrient utilization, antioxidant capacity, immune response as well as disease resistance in many aquaculture species.

Mechanisms have also been identified to enrich the nutritional value of insects, making them more effective as an aquafeed ingredient.

Besides, the low carbon footprint associated with their production makes them an even more interesting protein source candidate in aquafeed.

However, there are still many areas that require further investigation to fully understand the utilization and benefits of insects in aquafeed.

6. PROSPECTS

Despite the promising results reported from the inclusion of insects as ingredients in aquafeed, important gaps still exist concerning their full utilization in aquaculture. For example, the majority of effects of insect utilization in aquafeed reported so far have important biases towards adult species. A large gap still exists with regards to the effects in the initial ontogenetic stages of fish such as embryos, fingerling and larvae. Additionally, the insect requirement levels in aquafeed for different aquatic animal species and stages of development under different culture systems are unclear. This knowledge is very important for commercializing the utilization of insects in aquafeed.

Also, given the numerous insect species currently reported as ingredients in aquafeed, there is a need to explore value addition methods during biomass production to improve the nutritional value. This will ensure the diets are easily utilized by the aquatic animals while reducing waste in culture facilities. Emerging studies show that different parts of insects such as meal, oil, pulp and paste can be used in aquafeed. However, the majority of studies in the literature have focused on insect meals to a larger extent and oils to a lesser extent, while very little is known regarding the utilization of pulp and paste.

Furthermore, important bioactive compounds such as chitin, fatty acids and antimicrobial peptides have been reported in insects, however, their role in aquatic animal growth and physiology is not very clear.

Besides, chitin has shown detrimental effects at higher insect inclusion levels in the diets of aquatic animals.

Future studies are required to explore how different parts and compounds of insects could be utilized in aquafeed.

Finally, studies evaluating the effect of insects on flesh safety and quality of fish and other aquatic food for human consumption are necessary. Addressing these gaps is relevant for the commercialization of insect utilization in aquafeed.

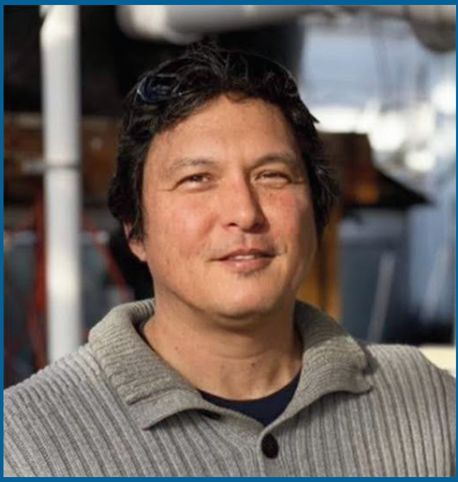
(Note : Issue 1, Volume 2 of the year 2024 describes in detail chitinase and its role in improving the nutritional value of insect meals in aquaculture feeds).

Source : Maulu S, Langi S, Hasimuna OJ, Missinhoun D, Munganga BP, Hampuwo BM, Gabriel NN, Elsabagh M, Van Doan H, Abdul Kari Z, Dawood MAO. Recent advances in the utilization of insects as an ingredient in aquafeeds: A review. Anim Nutr. 2022 Aug 8;11:334-349. doi: 10.1016/j.aninu.2022.07.013. PMID: 36329686; PMCID: PMC9618972.

THE RESTRAINING FACTORS OF TRANSFORMING THE AQUACULTURE WITH INSECT-BASED FEED

By : Dr Vimal Selvaraj is a professor of Integrative Physiology in Cornell University's Department of Animal Science, combines his veterinary background with a deep commitment to enhancing livestock-based food systems sustainably.
His work spans fundamental physiological mechanisms and practical farming and management applications, aims to boost farm efficiency. Notably, his research has explored converting dairy waste into housefly larva meal for aquaculture, highlighting the potential of insect-based feeds in promoting One Health. He actively engages in collaborations to refine production methods and investigate the values in insect-based feed.

Corresponding author: vs88@cornell.edu



And Dr Eugene Won is a Sr. research associate in the Animal Science Department at Cornell University, performs aquaculture and fisheries research, teaches courses on fish biology and production, and serves as Academic Coordinator for Shoals Marine Lab. He runs a recirculating aquaculture/aquaponics research lab designed to develop and test novel, sustainable aquafeed systems capable of salvaging nutrients from industrial byproducts (e.g., seafood processing discards and insect larvae) or other liabilities (invasive species). He works across the disciplines to prosper collaborative research relationships with commercial aquaculturists and other seafood producers (fishermen, seafood dealers, and processors), academics and government agencies.

Insect farming presents a sustainable solution for aquaculture feed, with a potential to transform feed production in the face of global food security challenges.

But, the sector faces challenges in economically scaling production, ensuring safety, and formulating regulations, pointing to the need for strategic solutions.

This article calls for focused research, investment, and innovation in insect-based feeds to meet aquafeed demands and maximize its environmental benefits.

The first explorations into utilizing insects as a food source due to the foresight of impending food demand occurred in the 1930s, the period between the world wars (Bodenheimer, 1951).

By the 1980s, more structured research underscored the tangible advantages of incorporating insect larvae into animal and aquaculture feeds (Newton et al., 1977; Bondari and Sheppard, 1981, 1987).

Nonetheless, the progression of applications from these investigations was overshadowed at the time by abundant, high-quality protein from marine sources (Green, 2016).

Fishmeal dominated the feed industry and became the primary protein source for various farm animal diets. In 1980, fishmeal production, totaling 5.8 million metric tons, was predominantly allocated to feed terrestrial livestock, with poultry (49.8%) and swine (36.1%) being the major consumers. As wild marine fisheries reached their limits in the following decade, however, aquaculture—along with its demand for protein feed—rapidly grew to fill ever-expanding seafood markets. Aquaculture surpassed beef production in 2012 and, in 2020, the human population consumed more farmed fish (87.3 million metric tons) compared to wild-caught fish (70 million metric tons). In this same year, the aquaculture industry consumed 85% of the approximately 16 million metric tons of fish being processed for meal. [All fishmeal data from (FAO, 2022)].

With increasing fishmeal demand, several studies have highlighted a forage fish stock crisis unfolding due to overfishing as early as in the turn of the century (Worm et al., 2006; Costello et al., 2012). Today, fishmeal production remains unpredictable due to lower sustainable yields, variable environmental and climatic conditions, increasing fuel costs per tonnage of catch, and reduced quotas. For example, fishmeal supply in 2023 was 23% less than in 2022 due to a combination of factors (IFFO, 2024).

In addition to the environmental controversy around fishmeal, the unpredictable volatility and overall rise in fishmeal prices has led to increased interest in alternative ingredients; however, shortcomings in plant-based proteins (e.g., soy), especially for high-value carnivorous fish like salmon, have opened the pathway for aquafeed ingredients—or at least protein supplements—with more appropriate nutritional value, with insect meals among the most highly anticipated. Offering low land and water requirements alongside high feed-to-insect biomass conversion efficiency, insect farming has been touted as a sustainable protein source for animal feeds, namely as an alternative to conventional fishmeal and soy.

Insects are viewed favorably for their potential to reduce the environmental impact of aquaculture production by using existing organic waste streams as their main input. This aspect of insect production has been modeled as part of a circular economy for addressing food system challenges, including a lifecycle that could salvage nutrients from organic industrial byproducts, or redirect population-concentrated urban wastes towards enriching rural production (Figure 1).

However, as the race for market share is on, both areas of concentration and competition are diverse with various large-scale and small-scale insect manufacturers undertaking different strategies to expand their businesses at the present time.

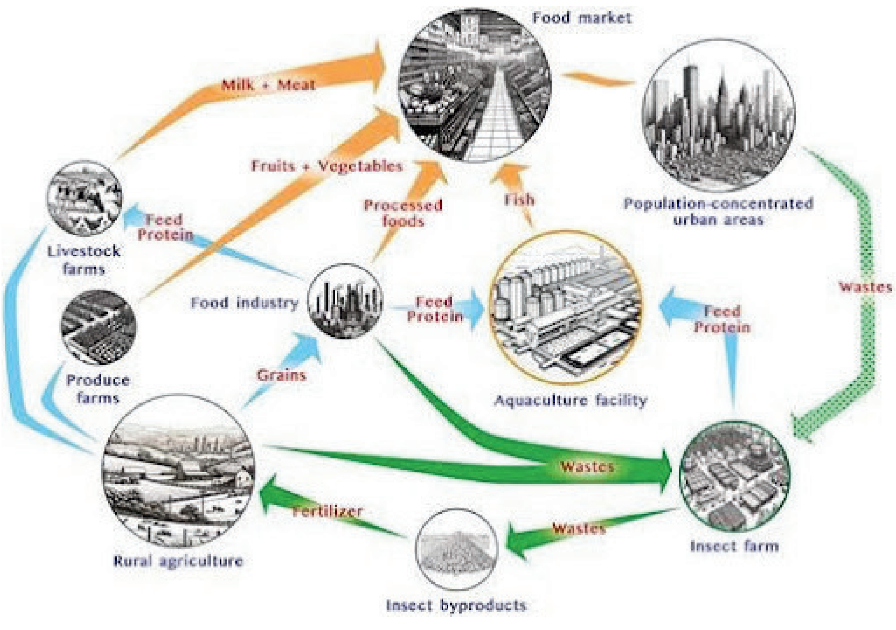


Figure 1.Insect-based feed industry integrated within a circular economy. This diagram illustrates an innovative insect protein production facility at the core of a circular economy model, efficiently utilizing urban and farm waste. In transforming underutilized resources into high-quality protein for aquaculture, and byproducts as fertilizer. This sustainable process can indirectly support the production of milk, meat, fruits, and vegetables, while generating additional revenue streams and mitigating waste disposal costs. This model demonstrates the feasibility and highlights the synergistic contribution to the food supply of human populations.

Arrows indicate flow of agricultural/industrial products (blue); waste streams (green); consumer goods (orange).

The FAO has endorsed insect farming as meeting the global demand for sustainable and environmentally acceptable protein for animal feeds and human food (van Huis et al., 2013). Different types of insects are already competing for a share in the aquafeed market. These include black soldier flies (BSF; Hermetia illucens), yellow mealworms (Tenebrio molitor), lesser mealworms (Alphitobius diaperinus), silkworms (Bombyx mori), locusts (Locusta migratoria and Schistocerca gregaria), crickets (Acheta domesticus, Gryllodes sigillatus, and Gryllus assimilis), and houseflies (Musca domestica). Among these, large-scale manufacturing is already in the pipeline for BSF and mealworms, which are considered the most versatile and efficacious for recycling waste materials into a commodity suitable for use in aquafeeds (van Huis, 2020).

The relative cost of insect meals nevertheless remains a factor yet to be determined until economies of scale can be assessed. With insect meal production just entering the industrialization stage, several issues still need to be addressed to determine if this commodity can be both economically and environmentally viable, including mass production scale, consistency of product quality, recognizing the full scope of products/byproducts and their markets, and regulatory challenges. There is no question about the fit for insect-based feed in aquaculture; performance and benefits have been extensively reviewed in recent literature with a core message being that insect meal can supplant substantial rates of soy and fishmeal in aquafeeds, with results contingent on the insect meal production methods and the fish cultivar in question.

RESTRAINING FACTORS

COSTS TO SCALING-UP QUANTITY

Economies of scale suggest that large facilities and automation will be needed to cost-effectively generate enough insect meal to impact the aquafeed market. Moreover, it needs to compete with the price point between soy meal ($570/metric ton; IndexMundi, end 2023), an inexpensive plant-based protein, and fishmeal ($1,870/metric ton), a high-quality animal protein; the latter being typically used at lower rates to supplement nutritional shortcomings of plant-based ingredients, especially for carnivorous fish. Currently, BSF meal is at a non-competitive price point between $2,000 and $5,000/metric ton (from industry communication).

Price notwithstanding, if the current volume of fishmeal used in aquafeed production represents a competitive market share opportunity for insect meal, then insect producers could arguably vie for about 4-5 million metric tons of product [about 85% of the 6 million metric tons of processed fishmeal produced in recent years; (IFFO, 2024)]. However, the largest operational BSF production facility claims only about 15,000 metric tons of annual BSF meal production.

So, even with planned facilities projecting three to four times that volume, production levels over the next decade may still be too modest to tangibly displace fishmeal demand from aquaculture, as almost 100 insect facilities at the scale of 50,000 metric tons per year would be needed to meet market needs represented by the current volume of fishmeal. Given this metric, the scope of insect meal can be toward reducing fishmeal use by supplementation. However, even for inclusion at 10%, larva meal would require the scale up for 500,000 metric tons/year in production. Aquaculture may also need to compete with other markets open to using insect products, including other animal feed industries and pet foods, that would also need to be considered in demand projections. Furthermore, at an estimated 5% conversion of food stock into insect meal in BSF cultivation, industries would need access to ~100 million metric tons of organic waste substrate to achieve production at levels comparable to the volume of fishmeal used for aquafeeds at the present time.

To address the need for economical feedstock, the industry needs to be gravitating toward a model of planning construction of insect production facilities in proximity to massive organic waste streams, to avoid resource input bottlenecks while decreasing transportation costs and carbon footprint.

To effectively scale up insect production, pivotal research must focus on comprehending insect physiology to inform biomimetic design and automation strategies.

By deepening our understanding of the biological processes at work, we can devise standardized, automated production systems that would enable substantial labor cost reductions over time.

Developing these systems requires dedicated research and development to address the complexities of rearing and harvesting insects on a mass scale.

Without this targeted investment in innovation, the industry will struggle to progress toward cost-efficient, large-scale operations.

INCONSISTENCY IN QUALITY

The quality of insect products can be affected at three main steps in the production process: the food provided, the time of harvest, and the method of processing larvae into meal.

The quality of substrates used for larval cultivation can significantly influence their composition and nutritional value as a feedstuff. This impact manifests both directly, as observed in alterations to larval lipid, protein content and amino acid profiles, and indirectly, through effects on larval growth and maturation rates, including developmental aberrations or delays induced by malnutrition. Likewise, development rate of ectothermic insect larvae is highly dependent on environmental temperature, such that optimal growth rate and harvest time can be assured only in controlled environments.

If not adequately provided by the grower, these factors can introduce compositional variability of the larvae that compromises consistency and complicates standardization across different insect farming companies. These considerations present additional challenges to ensuring outcomes in current larval farming operations and future plans for scale-up. Finally, heat pasteurization of larvae to kill potential pathogens, and/or overheating during drying stages, can reduce the product's nutritional value.

Beyond the proof-of-principle results, comprehensive farm-level aquaculture data collection over time would be important to rigorously assess insect protein-based aquafeed performance and provide feedback to insect producers to further refine their production methods. Implementing strategies that ensure consistent quality of feed stocks (that may need testing and supplementation), and environmental controls, adds a layer of complexity and costs to the production process.

UNKNOWN VALUE OF BYPRODUCTS

While the primary product of insect production is larva meal, other byproducts, such as frass and chitin, also accumulate during the process and are not without value. However, these insect byproducts are novel, and their actual market value is hard to determine in a production context that is yet speculative.

A business model that includes secondary revenue streams, in combination with offsetting byproduct disposal costs and downstream environmental impacts, could expand the scope of products leaving insect production facilities.

The means of extracting, processing, and transporting these products would need to be cost-effective, arguably justifying the need for further research to help insect producers assess the value of tangential business opportunities.

CONCERNS AND THREAT OF NEW PROBLEMS

Although there are a few studies evaluating the safety of insect meal in terms of contaminants and microbes, there are none on the safety issues surrounding the production process itself.

Biosecurity for an operation that is labor intensive can be a critical concern when dealing with decaying waste that might have frequent bacterial and mycotic blooms. Risk of infections, endotoxin/mycotoxin exposure, and allergens that could lead to health problems might need to be addressed. There is already a known concern that the waste substrates attract other species of flies to lay en route to larva cultivation facilities introducing undesirable larvae in the cultivation mix.

Such invasive larvae would affect consistency of insect meal quality. Moreover, some of these invasive flies that have a shorter of life cycle emerge prior to harvesting causing potential public health concerns. Addressing these problems at scale without added costs can be a challenge for this industry.

Another core concern is that of any intensive farming operation in that monocultures are susceptible to infections due to high-density populations and confined environments.

Factors associated with stress from suboptimal conditions and nutritional issues compounded by reduced genetic diversity might lead to elevated susceptibility and rapid spread of pathogens.

Over time, the industry might also see devastating emerging pathogens due to selective pressure and uniform host vulnerability. Therefore, genetics research to maintain populations through stock insect breeding schemes to stably sustain diversity would significantly reduce pathogen risks in the long run.

REGULATORY CHALLENGES

The regulation of insect-based ingredients currently varies significantly by region, creating a complex landscape for producers and farmers to navigate. Ensuring compliance with local and international standards is essential for widespread adoption. Production and use of insect meals for animal production is legal in the EU and the United States; however, there remains a lack of certainty regarding quality of substrates/waste streams that can be used for larval cultivation. Moreover, there are other regions outside the EU and the United States that do not seem to have undergone similar regulatory scrutiny.

Seafood, however, is a global commodity, with most aquaculture products exported from Asia, often from countries with different agricultural standards than the importing countries. Currently, this does not seem to be an issue but, with traceability and raw materials becoming more of a concern for environmental, labor, and health reasons, it is not out of the question that conflicting food production standards could lead to trade restrictions and significant hurdles for this growing industry.

CONCLUSION

The Need for More Research and Caution. In summary, like many forms of agriculture, breeding flies entails maintaining a delicate equilibrium between technological innovation and natural processes through biomimicry.

Key to success in this field is the ability to consistently induce mating among captive adults, construct specialized facilities, control operational expenses and fluctuating quality, secure customers open to shifting traditional practices, and invest in technology that enhances productivity and quality.

While several companies have entered the scene, the sector still lacks standardized methodologies and best practices, with much of its operations cloaked in secrecy as firms vie for market dominance.

Therefore, the need for speed given the broader urge for implementing such a system has not been met with academic engagement and federal support for scientific research on guiding possible improvements to the production process.

Moreover, addressing concerns without conflicts of interest need independent agencies and federal incentives that can address and highlight the safety and risks associated with the use of insect-based aquafeed.

Nevertheless, the prospect of utilizing insects as a sustainable, high-protein feed for livestock holds great promise, yet overcoming the substantial hurdles that remain is essential for this vision to materialize.

Source : Vimal Selvaraj, Eugene Won, Transforming aquaculture with insect-based feed: restraining factors, Animal Frontiers, Volume 14, Issue 4, August 2024, Pages 24–27, https://doi.org/10.1093/af/vfae011

INSECT FEED IN SUSTAINABLE CRUSTACEAN AQUACULTURE

Aquaculture is a growing global food production sector that aims to meet the increasing demand for dietary protein. Crustaceans are an important and predominantly high-priced aquaculture segment that could support the transfer of sustainable new technologies to other sectors.

Areas of interest include disease management and compound feeds, both of which have the potential to improve both the profitability and sustainability of aquaculture. Modern compound feeds are largely composed of fishmeal and/or terrestrial plant materials, the production of which is unsustainable, leading to the depletion of finite resources. Insects are a promising protein-rich alternative to fishmeal that can reduce the environmental footprint of aquafeeds and crustacean aquaculture.

First research data have shown that insect meal has a favourable nutritional composition with positive health effects, and is environmentally sustainable with a strong economic potential, particularly supporting circular economy by valorising otherwise unused sidestreams.

1. INTRODUCTION

Marine animal proteins are needed to support globally increasing food demands (FAO, 2018). In 2019, 120 million tons of fish, crustaceans, mollusks, and other aquatic animals contributed to global nutrition (FAO, 2021a). An additional 37.4 million tons are required by 2025, but deteriorating ecosystems will not support an increase in the sustainable foraging of aquatic species (Hua et al., 2019). The catch rate of global fisheries has remained largely stable since 1990, while aquaculture production increased from ~15 million tons in 1999 to more than 82 million tons in 2018, and further growth is anticipated (FAO, 2020). However, the expansion of aquaculture increases greenhouse gas emissions (Yuan et al., 2019).

The growth of aquaculture is projected to slow down between 2019 and 2030 due to stricter environmental regulations, the restricted availability of water and production locations, disease outbreaks exacerbated by intensified production, and lower productivity gains (FAO, 2020). Importantly, feed and energy consumption, and the discharge of effluents, are the main reasons why intensive and semi-intensive crustacean aquaculture is unsustainable, and these factors also govern profits (Cao et al., 2011; Marín-Riffo et al., 2021). Recent developments in the field provide promising avenues to improve the sustainability of crustacean aquaculture.

Modern technologies for water treatment and pathogen control can improve animal health and reduce water consumption, although such benefits are offset by higher energy demands (Ruiz et al., 2019; Zaibel et al., 2022). The availability of these cutting-edge technologies is mainly limited to premium target species. The demand for high-value species such as sustainably sourced shrimps is predicted to grow, unlocking new production locations in land-based systems, for example in Europe (FAO, 2020). Here, water-efficient recirculating aquaculture systems (RAS) can substantially reduce aquaculture's environmental impact, particularly when powered by renewable energy (Badiola et al., 2018). Furthermore, new insect-based compound feeds offer an alternative and sustainable source of proteins to improve health and enhance growth (Cottrell et al., 2020), but such feeds are not yet commercially available. Facilitated by high product prices, new technologies (including feeds) can be transferred to lower-priced species and regions, facilitating profitable and sustainable production.

Recent work on insect-based feed in aquaculture encompasses primarily fish data (Tran et al., 2022). However, given their broad phylogenetic and physiological differences, this review synthesises current developments in crustacean aquaculture and the potential for innovative and sustainable food production. First, we briefly describe current crustacean aquaculture systems. We then characterise commercial aquafeeds for crustaceans and compare the suitability of insect-based feeds. We next elaborate on recent crustacean health perspectives and assess the benefits conferred by insect-based feeds. To outline the economic and social framework, we then discuss the ecological and economic sustainability of aquafeeds and insect proteins, the current legal framework, and the

consumer acceptance of insect-fed crustacean products. We conclude by evaluating insect production for aquafeeds and its potential socioeconomic consequences.

2. CRUSTACEAN AQUACULTURE

Aquaculture is the controlled farming of freshwater and saltwater organisms (mariculture), including fish, mollusks, crustaceans and aquatic plants. Such organisms are usually farmed in ponds, tanks or raceways, using landbased (onshore), coastal (nearshore) or offshore facilities. Aquaculture can be traced back more than 4,000 years in China (Beveridge and Little, 2002) and its global importance is increasing (FAO, 2020; Tacon, 2020). Since 1960, annual fish consumption has outpaced world population growth driven by increasing incomes and the adoption of well-balanced diets. For example, the annual per capita consumption of fish increased from 9.0 kg in 1961 to 20.3 kg in 2017 (FAO, 2020, 2021b; Noguera-Muñoz et al., 2021).

Crustaceans account for 9% of production in the global aquaculture sector (Figure 1). Since 2000, crustacean production has grown continuously at an annual rate of nearly 10% (Tacon, 2020), reaching 10.5 million tons and a market value of US$ 276.6 billion in 2019 (FAO, 2021b).

Marine shrimps dominate the sector, followed by crayfish, crabs and prawns (Figure 1). Pacific whiteleg shrimp (Litopenaeus vannamei), Red swamp crawfish (Procambarus clarkii), Chinese mitten crab (Eriocheir sinensis), Giant tiger prawn (Penaeus monodon), Oriental river prawn (Macrobrachium nipponense) and Giant river prawn (M. rosenbergii) make up ~93% of global crustacean production (FAO, 2021a; Tacon, 2020) (Figure 1). Their market value ranged between US$ 5.64/kg (shrimps) and US$ 16.93/kg (lobsters and langoustes) in 2018 according to the FAO (FAO, 2021c). Similar to aquaculture in general, nearly 90% of farmed crustaceans are produced in Asia and most are also consumed there, with China alone producing 50% (Costa-Pierce and Chopin, 2021; El-Sayed, 2021; Naylor et al., 2021). The production of E. sinensis, P. clarkii and Portunus spp. (swimming crabs) is mostly restricted to China (FAO, 2021a). The increasing demand for aquatic products has driven the development of aquaculture systems.

For shrimps, the first extensive coastal pond culture was reported in 1957 (Lebel et al., 2002). Intensified production started in the 1980s and can be quantified by the degree of water exchange, aeration, input of (pelleted) feeds, fertiliser and medication, and the resulting yields (Lebel et al., 2002). Today's shrimp culture can be classified by the type of culture vessel (pond, raceway or tank), the type of water exchange system (open, semiclosed or closed), the relative stocking density, and the energy demand for water maintenance, feed and transport (extensive, semi-intensive, intensive or super intensive) (Figure 2).

Intensified production is associated with several challenges, often related to sustainability and the corresponding ecological, economic and social issues.

Traditional coastal shrimp farming in ponds has caused extensive mangrove deforestation (Noguera-Muñoz et al., 2021) and related ecological and economical losses (Walton et al., 2006). Accordingly, social licenses in aquaculture are being considered to improve community-industry relations (Mather and Fanning, 2019). Alternative in-land pond systems compete for space with agriculture and may intensify greenhouse gas emissions (Yuan et al., 2019). Stocking densities are increased to boost the economic output of semi-intensive and intensive pond cultures

compared to extensive ponds, which requires enhanced feeding and water quality management (aeration and water exchange) to ensure the better control of pathogens, parasites and pests.

Furthermore, intensified production in traditional systems increases the release of effluents that may lead to the eutrophication of adjacent ecosystems (Boyd et al., 2007).

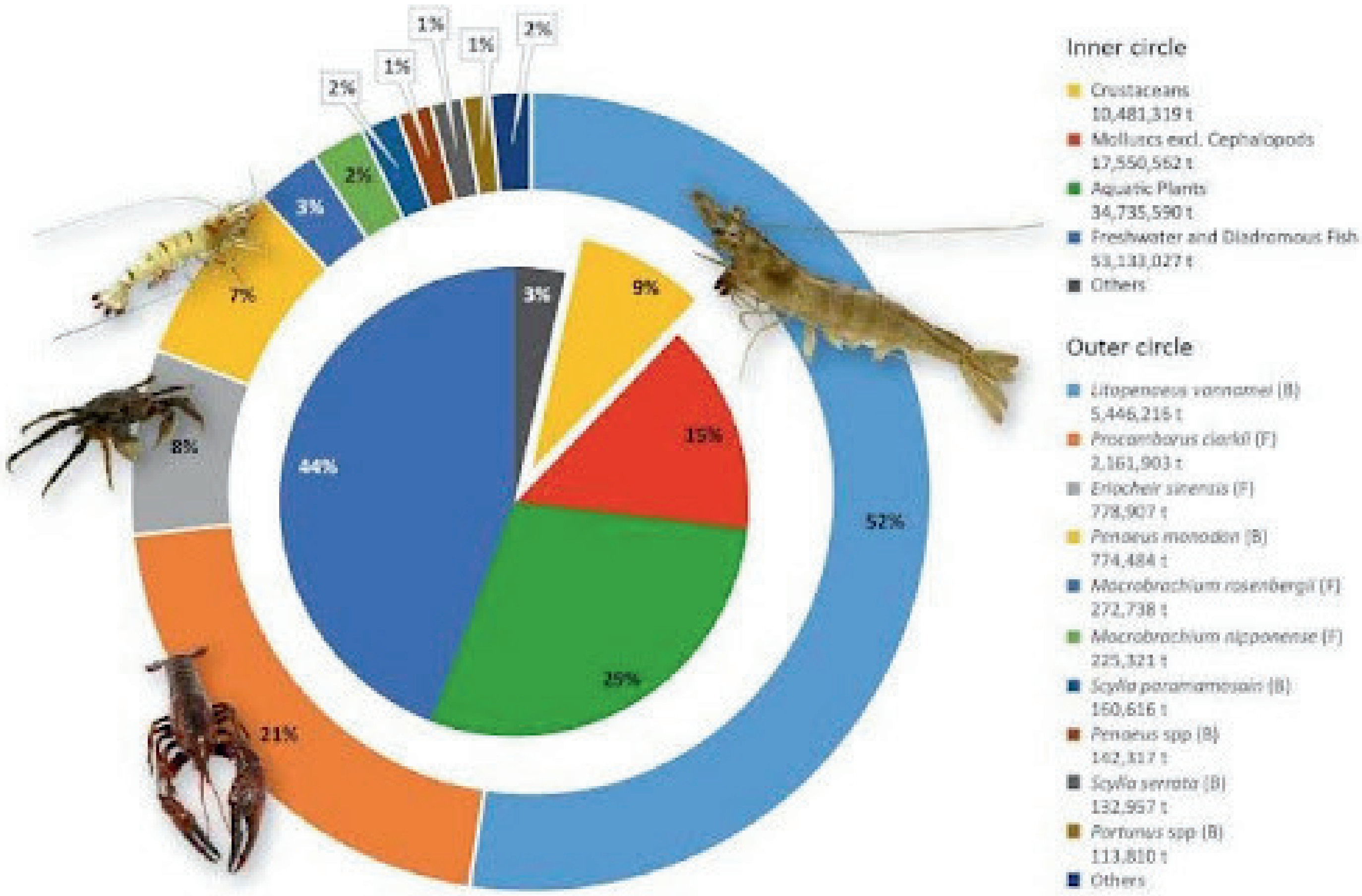


Figure 1. Global aquaculture production and main crustacean species in 2019. Inner circle represents total global aquaculture production in 2019 (120,098,422 tons, including 10,481,319 tons of crustaceans). Outer circle represents the 10 commercially most important crustacean aquaculture species (65 listed species). B = brackish and marine water; F = fresh water (data from FAO, 2021a).

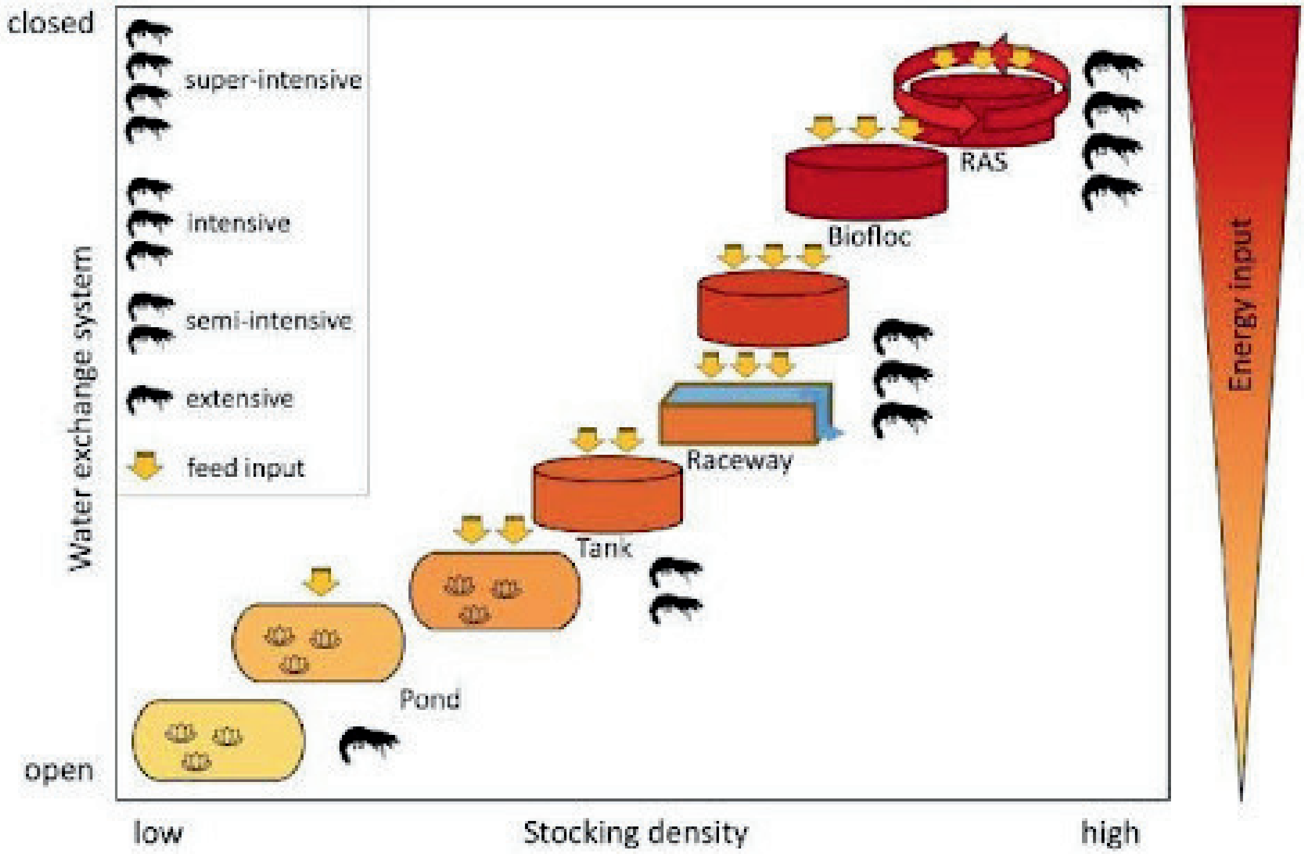


Figure 2. Crustacean culturing systems. Culture vessel (pond, raceway or tank), type of water exchange system (open, semi-closed, or closed/recirculating), and energy demand for water maintenance, feed and transport (extensive, semi-intensive, intensive or super-intensive). Stocking density is generally higher at higher intensities and feed inputs. RAS = recirculating aquaculture system.

In modern super-intensive crustacean aquaculture, water quality management and specific compound feeds are necessary to avoid the excessive discharge of effluents and to ensure good culturing conditions.

Furthermore, new technologies allow for 'smart aquaculture', a combination of artificial intelligence, Internet of Things technology, and traditional aquaculture (Hu et al., 2020; Mustapha et al., 2021).

For example, real-time monitoring of vitality and behaviour, risk prediction, and the control of physical and chemical parameters can optimise the health and growth of farmed species.

There are two main forms of super-intensive farming: clear-water RAS and biofloc. In the former, highperformance filters exchange less than 1% of the water per day by combining ammonia-removing biofilters and UV or ozone water sterilisers, although this involves high upfront investment costs and consumes a lot of energy (Badiola et al., 2018; Ray et al., 2017) (Figure 2 and 3). These costs can be offset in part by very high stocking densities, which in turn increase the risk of catastrophic failure due to disease (Naylor et al., 2021).

Therefore, disease management is a core element of modern aquaculture, including the development of specific pathogen free (SPF) broodstocks and (feed) additives such as antimicrobial peptides (AMPs), double-stranded RNA (dsRNA) and immunostimulants (Flegel, 2019). In contrast, biofloc technology encompasses aggregates of bacteria, algae or protozoa embedded in a matrix of particulate organic matter with a high carbon/nitrogen ratio.

When added to the culturing system, the mostly heterotrophic microbial communities respire carbon and incorporate bioavailable nitrogen, thereby avoiding harmful ammonia levels in the water and providing edible aggregates that consist of microbes, algae and protozoa for the cultured (crustacean) species (El-Sayed, 2021).

While the investment costs for biofloc systems are lower than those for clear-water RAS, the technology is only suitable for a limited number of species and the water quality is generally lower (Dauda, 2020; El-Sayed, 2021).

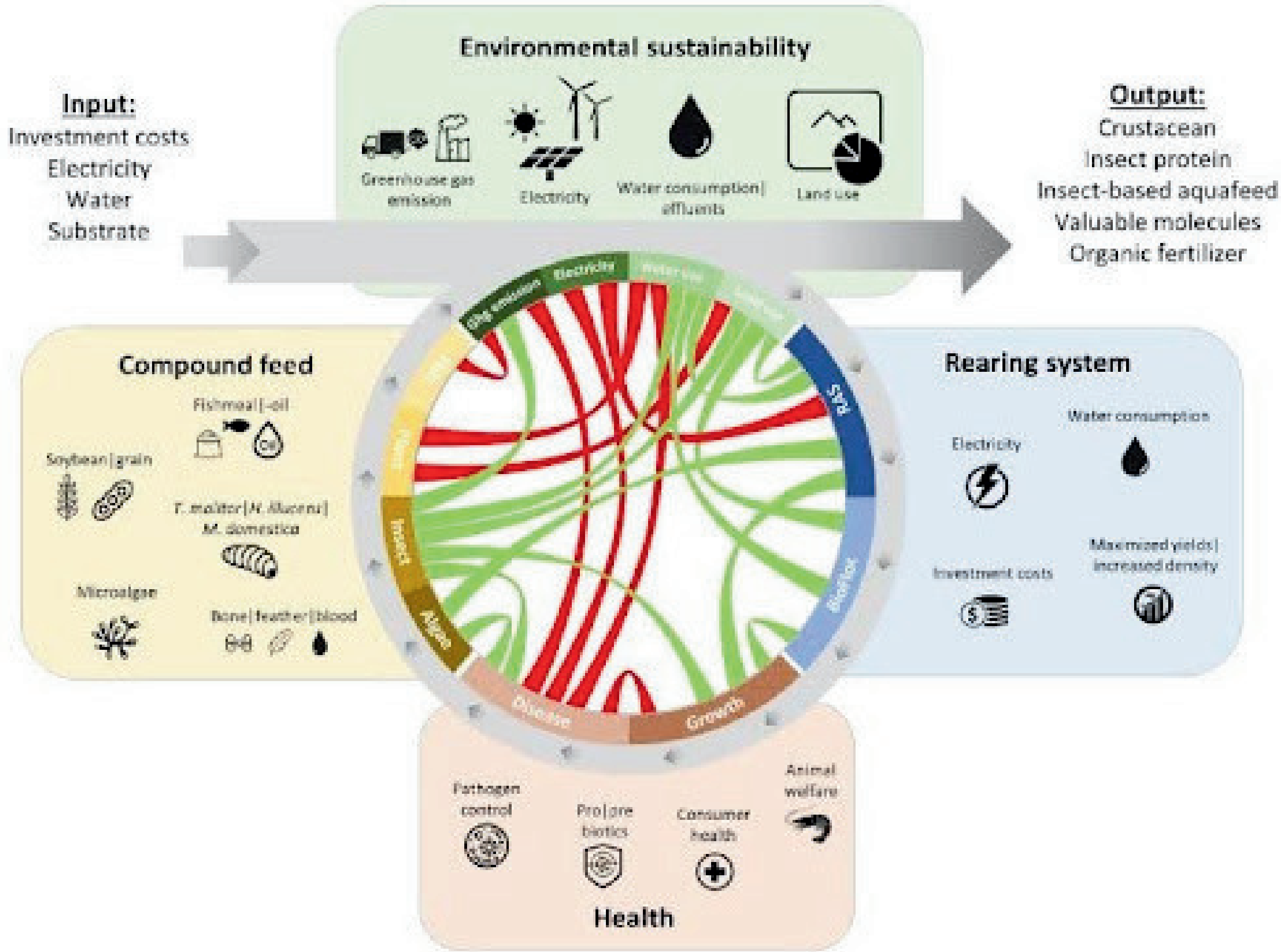


Figure 3. Conceptual overview of sustainable, insect-based crustacean aquaculture. Specific features of the rearing system, health aspects and aquafeed compounds affect each other, the environmental sustainability of production, and the overall profitability of the value chain (gray arrows). All these factors are further governed by legal and socioeconomic restrictions (not displayed). Interactions with positive and negative effects on profitability and/or sustainability are represented by green and red arrows, respectively. Ghg = greenhouse gas; RAS = recirculating aquaculture system.

Modern (crustacean) aquaculture systems can increase production while reducing water consumption, effluents and land use (Figure 3). However, it is important to acknowledge that the high costs of such systems currently limit them to wealthy countries, which contribute a negligible fraction to global crustacean production.

Unlike expensive technologies, compound feeds – once developed – are more readily available. Such formulations can reduce costs, enhance yields, limit greenhouse gas emissions and thus help to conserve marine resources (Badiola et al., 2018; Cortés et al., 2021; Shah et al., 2018; Verbeke et al., 2015; Yuan et al., 2019; Ziegler et al., 2013).

3. INSECTS IN AQUACULTURE FEED

COMPOUND FEED

Fed aquaculture accounts for 69.5% of global aquaculture and nearly 90% of crustacean aquaculture (Malcorps et al., 2019). Production relies largely on formulated compound feeds (FAO, 2020), which represent 50-70% of total production costs (Ferrer Llagostera et al., 2019; Gong et al., 2019). State-of-the-art aquaculture feeds contain proteins (including essential amino acids), carbohydrates, fats (including polyunsaturated fatty acids, PUFAs), vitamins, minerals and pigments (Ansari et al., 2021; Hua et al., 2019). Depending on species and life stage, the composition is adjusted to meet macronutrient and micronutrient demands, maximise growth, and promote health to yield high-quality and safe products that meet consumer requirements (Ansari et al., 2021; Hua et al., 2019). Further additives include functional feed components that reduce oxidative stress, boost appetite or confer disease resistance (Hua et al., 2019). Typical functional feed additives include vitamins, PUFAs and highly unsaturated fatty acids (HUFAs), amino acids (e.g. methionine), carotenoids, prebiotics and probiotics.

The key challenge in the development of sustainable aquafeeds is their reliance on fishmeal and fish oil, which are not environmentally friendly (Checkley et al., 2017; FAO, 2016, 2018; Froehlich et al., 2018; Pauly and Zeller, 2016) and particularly crustacean aquaculture has been a major consumer (27.5% of total fishmeal fed in aquaculture in 2003) (Tacon et al., 2006). Alternative compound feeds are often unsustainable, unavailable in sufficient amounts, or too expensive. Proteins contribute most to these costs because feeds must include large amounts of high-quality protein (Ansari et al., 2021) (Table 1). Protein sources must provide an adequate amino acid profile while also ensuring digestibility and palatability (Sánchez-Muros et al., 2020). Depending on species and age, the standard formulation of shrimp feed, for example, consists of 35-50% proteins (National Research Council, 2011) and 6-14% lipids (Ayisi et al., 2017b). Potential alternatives to fishmeal and fish oil include plant-based proteins, animal by-products, algae, yeast and insects.

Plant-based feeds may provide a good source of protein although many are characterised by unbalanced amino acid profiles, a low protein content, anti-nutritional factors, or low attraction and palatability. Soybean meal is often included in aquafeeds and offers digestible, high-quality protein with a beneficial amino acid profile at low cost (Jatobá et al., 2017). However, it cannot fully replace fishmeal and is also considered unsustainable, particularly because large areas of land are needed for soybean cultivation (Gil-Núñez et al., 2020; Sánchez-Muros et al., 2020). Terrestrial plant materials for aquafeeds generally intensify the pressure on agricultural resources by increasing the demand for fresh water, land and fertilisers (Richardson et al., 2021). In aquaculture, the nutritional properties of animal protein sources are considered superior to those of plants, including better digestibility, more suitable amino acid profiles, the absence of anti-nutritional factors, and a higher crude protein content (Sánchez-Muros et al., 2020). However, the essential amino acid and fatty acid profiles of blood meal, hydrolysed feather meal and poultry by-product meal, for example, differ from those of marine sources and are only partly suitable as aquafeeds (Bandara and Tharindu Bandara, 2018; Sánchez-Muros et al., 2020).

In addition to proteins, PUFAs and HUFAs are recognised for their health benefits in crustaceans and humans (Patnaik et al., 2006). Currently, only microalgae provide a comparable omega-3 fatty acid profile to fish oil for crustacean nutrition (Cottrell et al., 2020). Some microalgae synthesise HUFAs such as eicosapentaenoic acid and docosahexaenoic acid, which promote sustainable production (Ansari et al., 2021) and confer digestibility and palatability (Han et al., 2019). Natural pigments from microalgae, such as astaxanthin, chlorophyll and carotenes, promote shrimp growth, and (in the case of astaxanthin) confer the pink flesh colour in cooked shrimp (Han et al., 2019)

Microalgae as an additive or substitute for fishmeal have positive effects on crustacean growth and quality, and achieve a favourable feed conversion ratio (FCR) (Cottrell et al., 2020; Ju et al., 2012). The environmental impact of microalgae is lower than that of terrestrial plants, fishmeal and fish oil (Beal et al., 2018). They also provide additional benefits such as oxygen production, CO2 fixation, water quality improvement and disease control (Charoonnart et al., 2018; Han et al., 2019; Nie et al., 2020) (Figure 3). Although microalgae are essential in crustacean hatcheries, their current low global production volume covers only 0.7% of the demand and therefore critically limits their use as a major component in crustacean feed (Oostlander et al., 2020; Sánchez-Muros et al., 2020).

Bacteria, yeast and insects are other alternatives that can be used as additives or major protein sources in aquafeeds.

Bacteria and yeast have high protein contents and amino acid profiles comparable to fishmeal (Hua et al., 2019). Indeed, bacterial components in aquafeeds constitute the functional base of biofloc technology. Furthermore, microbial bioactive products can reduce the amount of fishmeal required in the diet of the carnivorous Black tiger shrimp (Penaeus monodon), but they are expensive (Hua et al., 2019) and dose control is important (Cottrell et al., 2020). Yeast derived from hydrolysed lignocellulosic biomass is also suitable for carnivorous species such as Atlantic salmon and Rainbow trout, but methionine supplements are necessary. Insects are considered a promising source of animal protein for human consumption and animal feed. They have a suitable nutritional profile and can be produced sustainably by utilising and valorising organic side-streams (Cottrell et al., 2020; Hua et al., 2019).

INSECT-BASED CRUSTACEAN FEED

Aquafeeds must promote growth, maintain health and ensure consumer safety (National Research Council, 2011; Tacon and Metian, 2008). Crustacean compound feed consists of 20-50% fishmeal that contains high levels of digestible essential amino acids such as methionine, lysine and leucine (Cummins et al., 2017; Henry et al., 2015; Sánchez-Muros et al., 2020) (Table 1). Fishmeal replacement can lead to a higher FCR, where more feed is required to achieve a given weight gain. This is particularly relevant for bacteria, yeast and macroalgae, whereas moderate inclusion of microalgae and insects seem to have little impact on the FCR or even reduce it (but see Cai et al., 2022), thus achieving greater feed efficiency especially at moderate replacement levels (Cottrell et al., 2020; Sánchez-Muros et al., 2020). Incorporating insects into compound aquafeeds is a novel approach even though insects are part of the natural diet of many fish (Howe et al., 2014; Whitley and Bollens, 2014) and crustaceans (Muangyao et al., 2019). Insect supplements improve growth, gut health and immunity, although a high content of insect meal can be detrimental (Table S1) (Cummins et al., 2017; He et al., 2022; Wang et al., 2021, 2022). Specific effects depend on the processing method, feed composition and insect/crustacean species.

Insects are highly diverse (Stork et al., 2015) thus offering many candidate aquafeeds with different characteristics in terms of nutritional composition. Insect species requirements are important when considering the design of their farms at appropriate scales. A wide range of insects has traditionally been used for food and feed, especially in Asia. In contrast, modern industrialised approaches have focused on a few well-characterised species including the Black soldier fly (Hermetia illucens), the Yellow mealworm (Tenebrio molitor), the Housefly (Musca domestica) and the House cricket (Acheta domesticus), all of which can be produced at large scales. H. illucens in particular is becoming more commercially attractive because it can reproduce rapidly, grows on a broad range of substrates, and has low potential as a disease vector (Müller et al., 2017; Wang and Shelomi, 2017). The nutritional composition of insects varies depending on species, life stage, rearing conditions and diet, and the protein content is generally similar to that of fishmeal (Freccia et al., 2020). On average, the protein content of insect meal is 50-82% dry matter depending on the species and processing method, compared to ≤73% in fishmeal and ~50% in soybean meal (Henry et al., 2015).

The lipid content of insects is generally high (10-49%) (Makkar et al., 2014) and is influenced mainly by diet and species (Galassi et al., 2021; Taufek et al., 2021; Van Huis et al., 2020).
As a replacement for fishmeal, 20 years of research focusing on insects in fish aquaculture has yielded promising results, whereas insect meal in crustacean aquaculture has received comparatively little attention (Alfiko et al., 2022; Hua et al., 2019). As of July 2022, 31 peer-reviewed studies are listed in the Web of Science (https://www.webofscience. com; keywords: 'crustacean', 'insect', 'aquaculture', 'Hermetia', 'Tenebrio', 'Litopenaeus', combinations thereof, and literature citing the appropriate hits/publications), which were published from 2013 to 2022 (Table S1). Most data have been generated for L. vannamei. In this species, fishmeal can be fully replaced with T. molitor meal without detrimental effects, whereas high proportions of H. illucens, M. domestica or the Domestic silk moth (Bombyx mori) can hamper growth and affect health (Chen et al., 2021a; Choi et al., 2018; Cummins et al., 2017; De León-Ramírez et al., 2018; Huang et al., 2020; Rahimnejad et al., 2019; Wang et al., 2021). For example, insect meal can affect the fatty acid composition of crustaceans (Shin and Lee, 2021), and a high proportion of insect meal can lead to hepatopancreatic damage in shrimps, potentially driven by the high lipid content and particularly by monounsaturated and saturated fatty acids (Chen et al., 2021a,b; Cummins et al., 2017; He et al., 2022; Wang et al., 2021). Defatted H. illucens meal was able to replace 60% of the fishmeal without negative effects in L. vannamei compared to <30% for full-fat insect meal (Chen et al., 2021a; Hu et al., 2019b; Wang et al., 2021). This demonstrates that postprocessing techniques can influence the nutrient composition and quality of the product and its suitability as a feed (Ravi et al., 2020). The amino acid composition of insect meal also influences crustacean growth. The essential amino acid methionine seems to be a limiting factor in L. vannamei because fishmeal could only be fully replaced with insect meal if methionine supplements were also provided (Cai et al., 2022; Motte et al., 2019; Panini et al., 2017b). Importantly, 100% replacement of fishmeal with insects in crustacean aquaculture is possible if these species-dependent constraints and feed processing options are considered.

At low supplementation rates, insects seem generally beneficial for crustaceans and can be considered as a form of functional feed (Table S1). For example, compound feed containing ~15% H. illucens and 25% T. molitor meal improved the growth parameters of L. vannamei (Choi et al., 2018; Cummins et al., 2017; Motte et al., 2019; Richardson et al., 2021; Shin et al., 2020). Even 1% H. illucens meal significantly improved the palatability of the compound feed (Terrey et al., 2021). Positive effects on crustaceans such as the Longarm river prawn (Macrobrachium tenellum), Danube crayfish (Pontastacus leptodactylus), Smooth marron (Cherax cainii), Australian red claw crayfish (Cherax quadricarinatus) and M. rosenbergii were also observed when they were fed on insects, including other species such as Trichocorixa sp., M. domestica, B. mori, Two-spotted cricket (Gryllus bimaculatus), Japanese rhinoceros beetle (Allomyrina dichotoma), Short-horned grasshopper (Oxya chinensis) and Protaetia brevitarsis (De León-Ramírez et al., 2018; Foysal et al., 2019, 2021; Martínez-Córdova et al., 2013; Mazlum et al., 2021; McCallum et al., 2021; Peh et al., 2021; Shin and Lee, 2021; Wang et al., 2022) (Table S1, Figure 3). Although the precise mechanisms have not been identified in crustaceans, there is ample evidence that insect supplements confer growth and health benefits (Table S1). Insects can therefore be considered as promising alternative protein sources for aquaculture (Hua et al., 2019; Sánchez-Muros et al., 2020).
Two key challenges are associated with the development of insect-based aquafeeds. First, the compound feed must be customised for each target species. Comparable data are still scarce for crustaceans (Table S1), but juvenile Mirror carps (Cyprinus carpio var. specularis) showed negative effects when more than 50% of the fishmeal was replaced with H. illucens meal (Xu et al., 2020), whereas African catfish (Clarias gariepinus) can effectively utilise replacements up to 75% (Fawole et al., 2020). The natural food regime of the target species (e.g. omnivorous versus carnivorous) may be an important determinant of the optimal supplementation rate. Second, a consistent and high quality is required for insect-based feed to achieve efficient growth and maximum yields.

In addition to postprocessing (see above), the substrate fed to the insects is a major determinant of meal composition, especially the lipid content and fatty acid spectrum (Ewald et al., 2020; Hopkins et al., 2021; Schreven et al., 2020; St-Hilaire et al., 2007), the protein content and amino acid spectrum (Fuso et al., 2021; Meneguz et al., 2018; Tschirner and Simon, 2015), and the mineral content (Chia et al., 2020).

Accordingly, insect species, substrates and post-processing must remain consistent to ensure the production of stable, high-quality compound aquafeeds. Compound feeds must also ensure consumer safety. In this context, insects could affect consumer health in two ways. First, insect-associated substances or pathogens could accumulate in the crustacean and have detrimental effects in humans.

Specifically, the contamination of substrates can lead to toxin accumulation in insects (Purschke et al., 2017). Cadmium, arsenic and lead can accumulate in T. molitor and H. illucens larvae (Diener et al., 2015; Van der Fels-Klerx et al., 2018; Vijver et al., 2003), whereas other heavy metals, mycotoxins and pesticides seem to pose a lower risk (Purschke et al., 2017).

Production methods, substrate, stage of harvest, insect species, and processing may all affect the presence and concentration of biological (microbes) and chemical (toxins and heavy metals) contaminants in insectbased feeds (EFSA, 2015). It is therefore necessary to monitor insect production and particularly the substrate, especially for cadmium and lead (Diener et al., 2015). In many jurisdictions, the monitoring of such substances in feed products is already required by law, as in the European Union (EU Regulation (EC) No 178/2002). Second, insects can directly or indirectly affect crustacean health and cause disease, which in turn may affect consumers. For example, microbial pathogens that are either associated with insects or introduced during farming and processing may impair shrimp health and consequently harm consumers. For consumers, the risk of insect-derived pathogens is generally regarded as low, in part because insects are phylogenetically very different to higher animals and humans (EFSA, 2015). However, insect pathogens can nevertheless hamper insect production (Eilenberg et al., 2018), despite the broad resistance demonstrated by H. illucens (Joosten et al., 2020). In principal, insects can also act as pathogen vectors for crustaceans, however examples of such terrestrial pathogen transmission to aquatic systems are rare (but see Stentiford et al., 2009), limited by differences in transition modes, a lack of host-parasite coevolution and a generally high pathogen specificity (McCallum et al., 2004).

Data on pathogen transmission via insect-based aquafeeds should be carefully considered, but are lacking at large. To be approved in the EU, insects for aquafeed must not be pathogenic or have other adverse effects on plant, animal or human health, for example by acting as pathogen vectors (EU Regulation No 2017/893). H. illucens can even reduce the pathogen load in aquafeeds (Swinscoe et al., 2019) and increases disease resistance in crustaceans (Table S1). Furthermore, given that most economically relevant crustacean diseases appear to be caused by marine pathogens (Shinn et al., 2018), replacing marine compounds such as fishmeal with insect meal should enhance disease management and reduce disease risk particularly in landbased aquaculture (Figure 3). Thus far, only a few insect species have been considered as crustacean feed, with most of the available data concerning H. illucens, T. molitor and L. vannamei. Based on the relevant literature (Table S1), it is reasonable to assume that the proportion of insect meal can be increased further and can eventually replace fishmeal completely. To this end, it is important to consider growth and health benefits –even at low supplementation rates – beyond the fulfilment of nutritional requirements.

4. SUSTAINABILITY

SUSTAINABILITY OF AQUAFEEDS

Aquafeeds account for ~90% of the environmental impact of fed aquaculture (Little et al., 2018). The most common proteins in aquafeeds – fishmeal and soybean meal – raise several environmental, economic and social challenges. Globally, 34% of fish stocks are harvested unsustainably and almost 60% at maximum capacity (FAO, 2020), leaving no room for sustainable increases in fish supplies for fishmeal. From a social perspective, the increasing consumption of fish by the middle classes is often addressed by rerouting resources, particularly small fish, from the poor and vulnerable (FAO, 2015; Isaacs, 2016; Tacon and Metian, 2009). Wild fish production declined by 26.5% between 2000 and 2018 (Jannathulla et al., 2019) and is expected to reach its ecological limits by 2037 (Froehlich et al., 2018). To provide sufficient fishmeal, additional sources, including fish residues (offal, trimmings and cuttings) now contribute ~30% of the global supply (FAO, 2020). However, the processing of bones, heads and tails results in lower-quality meal and higher consumption rates (Hua et al., 2019). Aquaculture consumes more than 70% of all the fishmeal and fish oil currently produced (Hua et al., 2019). Globally, fishmeal production uses ~15 million tons of whole fish (Terrey et al., 2021), and the demand for feed is projected to surpass fishmeal availability by 2050 (Froehlich et al., 2018).

Fishmeal alternatives are already widely used, including soybean, which offers comparable nutritional properties. Although the nutritional value of soybean meal is much higher than many other plants (National Research Council, 2011), its environmental footprint is unfavourable. Soybean production is very land-intensive (Lathuillière et al., 2017), adding to the already large area required for conventional shrimp aquaculture (Davis et al., 2021).

SUSTAINABILITY OF INSECT PROTEIN

Compared to fishmeal and soybean meal, insect proteins have the potential to improve the overall sustainability of aquafeeds (Hua et al., 2019; Liland et al., 2021) (Figure 3). The aspect of insect production that contributes most to global warming is energy consumption, so renewable energy and industrial waste heat can improve sustainability where available (Salomone et al., 2017). Although insect production systems are a source of greenhouse gas emissions (Parodi et al., 2020), the carbon footprint is low compared to fishmeal and soybean meal (Perednia et al., 2017) because local insect production removes the 30% of emissions caused by global shipping (Mertenat et al., 2019). The use of agricultural by-products and food industry side-streams as substrates for insect mass production is also advantageous (Tschirner and Kloas, 2017), and the ability to recover otherwise lost nutrients from these substrates is major contribution to sustainable protein production (Magee et al., 2021; Van Huis et al., 2020). Many proposed input substrates are decomposed naturally by microbes, emitting 70% more CO2 equivalents than nutrient valorising by insects (Perednia et al., 2017; Smetana et al., 2019). The valorising of by-products thus further compensates for the environmental impact of the main product (in this case crustaceans) (Kim and Kim, 2010)

6. THE LEGAL FRAMEWORK AND CONSUMER ACCEPTANCE

Insect production is growing and becoming increasingly industrialised (Wade and Hoelle, 2019).The success of insect-based feeds will predominantly depend on consumer acceptance and regulatory approval, the latter differing widely across global jurisdictions.

For example, the EU has permitted the utilisation of proteins from seven insect species (H. illucens, M. domestica, T. molitor, A. domesticus, Tropical house cricket (Gryllodes sigillatus), Jamaican field cricket (G. assimilis) and Alphitobius diaperinus) as feed ingredients for aquaculture (EC Regulation (EU) 2017/893) and poultry and pig production (EC Regulation (EU) 2021/1372). In the USA, only one species (H. illucens) is an approved animal feed ingredient and the application of H. illucens larvae or meal is currently limited to feed formulations for salmonid aquaculture (Lähteenmäki-Uutela et al., 2021). In countries that traditionally endorse entomophagy, legislation is more open toward novel insect products. In China, a catalogue of approved raw feed materials compiled in 2012 lists insects and degreased insect powder (U.S. Department of Agriculture (USDA), 2021). Each product must be labelled by species, and meticulous hygiene and labeling standards must be met (Lahteenmaki-Uutela et al., 2017). The global regulatory disharmony is challenging for international producers, which must comply with different regulations depending on the location of their production facilities and customers. With nearly 90% of crustacean aquaculture located in Asia and over 50% in China (FAO, 2020; Naylor et al., 2021), the favourable local legislation facilitates the development of insect-based aquafeeds. The consumer acceptance of insect-based products may also pose a barrier (Onwezen et al., 2019). Consumer acceptance varies across the world. In the Global South (Latin America, Africa and South Asia), insects are part of the food culture and are consumed regularly by more than two billion people (Feng et al., 2018; Huis et al., 2013; Raheem et al., 2019).

Research data from the Asian markets are scarce, but the drivers of consumer acceptance appear similar to those in Western cultures (Liu et al., 2019; Park and Choi, 2020; Sogari et al., 2019a) and seem to depend mostly on availability, traditions, food processing/preparation, quality, price, and background knowledge, whereas the health risks of insects are rated low (Arena et al., 2020; Hamerman, 2016; Sogari et al., 2019c; Szendrő et al., 2020).

Beyond the Global South, insects are only just emerging as a novel food and are more regarded as pests and indicators of low hygienic standards, reducing consumer acceptance (Hartmann and Bearth, 2019; Sogari et al., 2019c). However, despite this attitude toward food, Western consumers are more amenable to insect feed in agriculture and aquaculture (Ferrer Llagostera et al., 2019; Rumbos et al., 2021)

Importantly, aroma and texture of aquaculture products are not affected by insect feeds (Cunha and Ribeiro, 2019; Gasco et al., 2019; Panini et al., 2017b).

7. OUTLOOK

Crustaceans are an important market segment that – based on their price – have the potential to drive the development of new sustainable technologies, such as disease management and alternative feeds. Compound feeds are essential for modern aquaculture but their ingredients, including fishmeal, fish oil and terrestrial plant materials, are often unsustainable, for example due to high water and land use, large carbon footprints, and the depletion of other resources. Therefore, sustainable aquafeeds offer a promising toehold to significantly improve the environmental impact and yields of crustacean aquaculture.

Existing data indicate that insect meal has a favourable nutritional composition as a fishmeal replacement for aquaculture, and offers health benefits, environmental sustainability and economic advantages, but there is an urgent need for research on the specific mechanisms of action.

On a global scale, all stakeholders strongly depend on more favourable legislation, communication, management, and controls along the value chain to intensify aquaculture yields and enhance sustainability (Joffre et al., 2018).

Given the current market size, insect-based feed will struggle to provide a global short-term solution. However, it offers the potential to improve production yields, disease management, environmental and social sustainability, arguing for the global intensification of sustainable crustacean aquaculture based on insect feed.

Source : Röthig, T., Barth, A., Tschirner, M., Schubert, P., Wenning, M., Billion, A., Wilke, T. & Vilcinskas, A., (2023). Insect feed in sustainable crustacean aquaculture. Journal of Insects as Food and Feed, pp.1-24.

NEWS

MRS ZAKIA DRIOUCH AT A MEETING TO SPEED UP THE COMPLETION AND IMPLEMENTATION OF ANDA MOROCCO'S MARINE AQUACULTURE PROJECTS

Ms Zakia Driouch, Secretary of State for Maritime Fisheries, examined ways of speeding up the development of marine aquaculture in Morocco and indicated that the National Agency for the Development of Aquaculture (ANDA) plans to increase the number of aquaculture farms to 232 by 2025, to achieve a production capacity of 115,900 tonnes and to create 2,720 direct jobs.

The plan aims to make accessible areas suitable for aquaculture, spread across the kingdom, to encourage investment in this promising sector, which offers opportunities to boost food security, stimulate investment, create jobs and generate significant added value. To achieve these objectives, the Secretary of State has called for the speedy implementation of support projects, particularly in the areas of taxation and training.

The Secretary of State for Maritime Fisheries has indicated that the National Agency for the Development of Aquaculture (ANDA) plans to increase the number of aquaculture farms to 232 by 2025. In a press release issued following a meeting held on Wednesday, Secretary of State Zakia Driouch underlined ANDA's objective of achieving a production capacity of 115,900 tonnes and creating 2,720 direct jobs. The plan aims to make suitable areas for aquaculture accessible throughout the kingdom, in order to encourage investment in this promising sector.

Ms Driouch highlighted the importance of aquaculture for Morocco, a sector boosted by the 'Halieutis' strategy initiated by His Majesty King Mohammed VI. This sector offers opportunities to strengthen food security, stimulate investment, create jobs and generate significant added value. To achieve these objectives, the Secretary of State has called for the implementation of support projects to be speeded up, particularly in the areas of taxation and training.

ANDA is also working on legislation to promote the sustainable development of the sector, notably through ten regional plans covering more than 2,300 km of Moroccan coastline.

These projects have increased the number of farms to 173, with an annual production target of 99,400 tonnes, and stress the importance of promoting aquaculture products to the Moroccan public and strengthening infrastructures to support young aquaculture entrepreneurs.

Zakia Driouch, Secretary of State to the Minister of Agriculture, Fisheries, Rural Development, Water and Forests, with responsibility for maritime fishing, held a working meeting on Wednesday at the headquarters of the National Agency for the Development of Marine Aquaculture in Rabat.

A working meeting devoted to identifying the agency's work programme and studying the mechanisms aimed at developing the marine aquaculture sector in Morocco and accelerating related projects, in the presence of the Director of the National Agency for the Development of Marine Aquaculture and several officials from the agency and the State. Secretariat in charge of maritime fishing.

The aquaculture sector in the Kingdom, initiated by the Halieutis plan, is one of the most promising sectors for the future and offers great potential to contribute to food security, create employment opportunities, stimulate investment, create added value and support the economy, in addition to the legislative and regulatory dynamic that the sector has witnessed over the last two decades.

which has provided a clear and straightforward vision for investors in mariculture throughout the national territory.

In this respect, and to ensure that the sector can continue its dynamism and contribute to meeting the challenges, particularly those relating to food security, stimulating and encouraging investment, creating employment opportunities and improving the sector's competitiveness, the Secretary of State gave instructions to accelerate the pace of implementation of programmes and projects relating to the aquaculture sector, keep pace with professionals, and motivate investors through... A range of procedures, particularly fiscal and financial, as well as the training and qualification of the workforce. She also called for a focus on completing all the legislative and legal texts currently under study, calling at the same time for concerted efforts by all partners to bring to fruition the structured programmes and projects linked to this subject. vital sector according to a precise timetable in line with the sound and far-sighted Royal Vision and in accordance with the content of the new development model and government programme.

In view of the great importance of aquaculture products at national level, the Secretary of State stressed the need to adopt a policy of communication and promotion of products from aquaculture farms in order to publicise them, especially as these are products that satisfy and meet all health safety conditions and standards.
It should be noted that the meeting included detailed presentations on the programmes and projects of the National Agency for the Development of Marine Aquaculture, as the Agency works to continue implementing the programme to develop marine aquaculture clusters in different regions of the Kingdom, as well as the programme to improve employment opportunities for young people and create a generation of entrepreneurs in the field of aquaculture. It is these projects that have enabled the sector to achieve continuous growth in terms of the number of agricultural projects that have been created, which include 173 farms, targeting a total production that will exceed 99,400 tonnes annually.

In addition to 61 other projects under construction for an annual production of around 24,800 tonnes and the creation of around 626 new direct jobs.

It should be noted that 10 regional marine aquaculture plans have been drawn up, covering more than 2,300 km, to ensure the sustainable development of the sector in 8 of the Kingdom's coastal regions, namely the Eastern Region, Tangier-Tetouan-Al Hoceima, Laâyoune-Sakia El Hamra, Casablanca-Settat, Marrakech-Safi, Massa, Guelmim-Oued Noun and Dakhla-Oued Eddahab. Among the structured projects on which the agency is currently working, there is also a programme to develop land-based marine aquaculture projects, particularly in remote areas not suitable for agriculture.

As part of the training and monitoring of projects in the aquaculture sector, the agency is continuing to download a set of programmes and technical support procedures for mariculture projects through 6 programmes benefiting 465 projects.
By 2025, the agency aims to increase the number of farming projects to 232, with a production capacity of around 115,900 tonnes, and to create 2,720 direct jobs.

Areas available for aquaculture will be advertised in several regions of the Kingdom, with the aim of attracting more investors to the sector.

As part of the digital transformation of the aquaculture sector, the government authority in charge of maritime fishing is endeavouring to keep pace with the National Aquaculture Development Agency in implementing workshops to speed up the digital transformation of its projects.

AFRICA FOCUSES ON THE FUTURE OF INLAND FISHERIES AND AQUACULTURE

From September 23 to 25, 2024, Dakar hosted the 20th session of the Committee for Inland Fisheries and Aquaculture of Africa (CIFAA).

This major event brought together representatives from 37 African countries, specialized agencies, and observers to discuss the challenges and opportunities in the sector, and advance aquaculture in Africa and facilitate knowledge exchange, policy alignment, and the promotion of sustainable practices across the continent. This session also highlighted the need to strengthen the resilience of these two sectors, supporting FAO's vision for blue transformation in Africa. The report reveals that inland fisheries produced 11.4 million tonnes in 2021, accounting for over 12% of global capture fisheries production, with a significantly lower environmental footprint than other protein-rich foods. Countries in the African Great Lakes sub-region contributed 12.2% of this global production.

Established in 1971, CIFAA is one of FAO's oldest regional fisheries commissions. Its mission is to promote sustainable fishing and strengthen cooperation among African countries.

The committee plays a crucial role in promoting research, establishing regulatory measures, preventing environmental damage, supporting fish farming, and improving education and training in inland fisheries and aquaculture.

As Africa faces growing challenges in food security and natural resource management, this 20th session of CIFAA marks a crucial step in defining the sustainable future of inland fisheries and aquaculture on the continent.

THE FUTURE OF FISH SAFETY AND TECHNOLOGY IN AFRICA: INSIGHTS FROM THE ANFTS 2024 GATHERING IN ZANZIBAR 13 NOVEMBER 2024

The African Network on Fish Technology and Safety (ANFTS) was held in Zanzibar, Tanzania, from November 12 to 14, 2024. The meeting's goal is to provide up-to-date information, stimulate research and technological collaboration, and strengthen national research capacity. It will also encourage the interchange and transfer of technology and information to promote the long-term growth of post-harvest operations in small-scale fisheries and aquaculture value chains.

The meeting will focus on decreasing and preventing aquatic food losses, improving aquatic food product safety, expanding national marketing channels, addressing social and gender issues, and comprehending climate change and environmental implications. Paper authors, the ANFTS Secretariat, representatives from relevant organisations, and FAO officials are all invited to participate.

The agenda covers various critical fisheries topics, including food loss and waste reduction, food safety, economic, social, and environmental sustainability, with sessions spread throughout three days.

On Day 1, following introductory remarks by FAO representatives, the Principal Secretary, and Hon. Shaaban Othman, Minister of Blue Economy and Fisheries – Zanzibar, participants were led through a series of keynote presentations.

Among them, Mrs. Hellen Guebama, Fisheries Officer at AU-IBAR, gave a keynote titled "Towards the Implementation of the Policy Framework and Reform Strategy in Fisheries and Aquaculture (PFRS) in Support of Fish Safety, Technology, and Marketing in Africa."

The presentation focused on AU-IBAR's strategic orientation in promoting sustainable fisheries practices throughout Africa, emphasising the PFRS' major pillars that define the continent's approach to fish safety, technology innovation, and market reform.

Hellen's observations highlighted AU-IBAR's role in integrating fish safety procedures with the PFRS's overarching goals, which include raising quality standards, encouraging technology adoption, and building resilient fisheries markets. In her presentation, Mrs. Guebama stated:

"To achieve the ambitious goals outlined in the PFRS, several strategic actions must be prioritized. These include strengthening market access through trade liberalization, improving product safety and traceability, and investing in the capacity building of traders and small-scale fishers.

The African Union's Agenda 2063, along with regional frameworks like the African Continental Free Trade Area (AfCFTA), will play a pivotal role in facilitating these reforms.

Collaboration with centres of excellence, the development of innovative technologies in fish production and processing, and the establishment of a unified African voice in international trade forums are critical to driving progress. As African countries continue to align their national policies with regional and global frameworks, the future of Africa's fisheries and aquaculture sector looks poised for sustainable growth, trade expansion, and enhanced food security."

The agenda has also included discussions about marine food loss and waste reduction, as well as presentations from international and local experts, followed by additional Q&A and wrap-up sessions. Day 2 will continue with lectures about food safety and nutrition, as well as quality considerations and innovative technology for safe fish processing. Sessions on economic sustainability will follow, with a focus on national and regional trade dynamics.

The afternoon will be focused on social sustainability, with a discussion on gender and social issues within fisheries value chains.

The day will wrap off with a discussion of climate change's impact on post-harvest fisheries and environmental sustainability.
The third day will involve a field trip to the Malindi fish market, followed by workshops on environmental sustainability after lunch.

The day will conclude with a special subject part focussing on innovations and case studies from the Caribbean and Pacific Islands. The meeting will end with the report being adopted and closing remarks delivered.

Source : AU-IBAR

EVENTS

AQUACULTURE AFRICA 2024 CONFERENCE (AFRAQ 2024) | 19-24 NOVEMBER 2024 | HAMAMET, TUNISIA

The 3rd Annual International Conference and Exhibition of the African Section of the World Aquaculture Society (AFRAQ24) will be held in Hammamet, Tunisia from November 19-22, 2024. The event will be hosted by the Ministry of Agriculture, Water Resources and Fisheries with the support of other national entities in Tunisia.
Tunisia, being one of the largest and fastest growing aquaculture producing countries in Africa, expects to receive thousands of delegates from around the world to celebrate achievements in all aspects of aquaculture development in Africa, but also to find solutions to some of the challenges that hinder the development of aquaculture in Africa. the growth of the sector and explore new opportunities in the field of the blue economy. AFRAQ24 will undoubtedly provide many opportunities for networking and collaboration.

Themed "Blue Agriculture: New Horizons for Economic Growth," the conference will highlight some of the latest research, innovations, and investments in aquaculture to support the continued growth of the aquaculture sector in Africa.

The event will include a scientific forum (oral and poster presentations), a trade show, industry forums, satellite workshops, student events, and other organized meetings. Renowned speakers from Africa and beyond are expected.

Visit Tunisia will also expose participants to some famous and interesting tourist attractions in Hammamet, the Mediterranean, and throughout the country.

Special aquaculture tours will be organized to nearby fish, shellfish, and seaweed farms – which are connected to fish processing, aquafeed, and R&D facilities.

THE SEAFOOD 4 AFRICA FORUM WILL BE HELD AT THE DAKHLA CONGRESS CENTER, MOROCCO FROM DECEMBER 4 TO 6, 2024

SeaFood4Africa Forum - Dakhla 2024: Dive into Knowledge with +15 Cutting-Edge Conferences.
From December 4-6, 2024, the SeaFood4Africa Forum at the Congress Palace in Dakhla, Morocco will not only bring together 150 exhibitors and 8,000 visitors but will also feature 10+ conferences focused on the most pressing issues and advancements in the seafood and fisheries industries.

These conferences offer unparalleled opportunities to learn from industry experts, discover new technologies, and explore sustainable practices shaping the future of the sector. Each session is designed to provide you with insights on the latest trends and challenges, from aquaculture innovations to global market opportunities.

Conference Highlights :

- **In-depth Discussions:** Gain insights into the most important issues in seafood and aquaculture, including sustainability, technological advancements, and regulatory trends.

- **Expert Speakers:** Engage with thought leaders and professionals who are driving innovation and change in the industry.

- **Practical Solutions:** Learn about new tools, processes, and strategies that can help your business stay competitive and eco-friendly.

- **Networking:** Meet and exchange ideas with conference participants, including researchers, industry leaders, and policymakers.

Don't miss this chance to stay ahead in Africa's seafood and fisheries industry by participating in 15+ conferences tailored to the challenges and opportunities shaping the future.

Dates: December 4-6, 2024

Location: Congress Palace, Dakhla, Morocco

Contact us now for more information:
t.chokry@seafood4africa.com
a.filaliansari@seafood4africa.com
h.ouardi@seafood4africa.com
+212 6 60 00 50 56

UNLOCK THE FUTURE OF AQUACULTURE AT THE AQUACULTURE BUSINESS GROWTH CONFERENCE - SEASON 2!

HOLDING DEC 11TH-13TH, 2024 IN NIGERIA

To explore sustainable innovations in aquaculture sector. This will be a deep dive into the future of Aquaculture, focusing on sustainable technologies, potential grants, scholarships, new alternatives in feed innovations, accessing finance, and key networking opportunities that can transform your business, career, and research in aquaculture industry today.

Join industry leaders and innovators as we explore sustainable technologies, groundbreaking feed alternatives, and opportunities for grants and financing. Networking opportunities to connect with investors and experts.

THE WAGENINGEN FISH NUTRITION WORKSHOP, FEBRUARY 2-6, 2025.

THE 4TH FISH NUTRITION WORKSHOP IS PLANNED FOR FEBRUARY 2-6, 2025.

Welcome to the FISH NUTRITION Workshop hosted by the Aquaculture & Fisheries group at Wageningen University & Research.

The **Wageningen Fish Nutrition workshop** is organized in February 2025 as the fourth of a series of annual Wageningen workshops on fish nutrition. As part of these workshops, leading experts in the field will give one-hour presentations, taking time to thoroughly introduce each subject.

This year's (2025) subject is **Fish Nutrition: Impacts on Gut Functioning and Health.**

The workshop includes two afternoons of hands on practicals on fish feed formulation and fish microbiota analysis.

Further, participants are asked to send an abstract of their research plans and to present a poster, with the best one awarded the poster prize. The official workshop language is ENGLISH.

OBJECTIVES

The objective of the present workshop is to provide participants with advanced knowledge on fish nutrition, focusing on gut physiology and health related aspects, as well as nutritional impacts on gut functioning.

During the workshop we will discuss the latest advances in fish nutrient requirements and sustainable sources, connecting them to fish physiology and health.

The use of novel tools in fish nutrition and the implication of microbiota and changes thereof will also be further discussed.

TARGET GROUP

The level of the workshop is targeting academic and company researchers as well as management staff in the aquaculture industry.

We more than welcome PhD students, who have a reduced registration fee.

For more information send an email to: nutritionafi.workshop@wur.nl

AQUAMOROCCO INTERNATIONAL CONFERENCE 2024

The Agadir Horticultural Complex will host the first AquaMorocco Conference on 28 November 2024. A flagship event for the Moroccan aquaculture sector, under the theme 'Towards sustainable Moroccan aquaculture', this conference is positioned as a catalyst for innovation and sustainability in the aquaculture sector.

AquaMorocco 2024 offers a unique opportunity to bring together key players in aquaculture, whether researchers, professionals or students. With a rich and varied programme, the conference will highlight scientific and technological advances, while providing a forum for enriching B2B exchanges. This event embodies Morocco's commitment to developing competitive and sustainable aquaculture, based on international best practice.

STRATEGIC CHALLENGES FOR MOROCCAN AQUACULTURE

With its world-renowned fisheries resources, Morocco is at a crucial turning point. Aquaculture represents an innovative response to the sustainability challenges exacerbated by climate change.

With more than half of the seafood consumed worldwide coming from aquaculture, the Kingdom has enormous potential to diversify and stabilise its blue economy.

AquaMorocco 2024 is part of this dynamic, offering a showcase for innovative farming systems, cutting-edge technologies and strategies for adding value to aquaculture products.

A programme designed by experts
The AquaMorocco 2024 programme has been carefully put together by a scientific committee of renowned national and international experts.

The presentations will cover the technical, economic and environmental aspects of aquaculture, with a focus on :

- Technological innovation for more efficient and environmentally-friendly farming systems.
- Diversification of species adapted to Moroccan conditions.
- Development strategies to conquer national and international markets.

SALON INTERPROFESSIONNEL DE L'AQUACULTURE DU CAMEROUN (SIAC2024)
DU 02 AU 07 DECEMBRE 2024
PALAIS POLYVALENT DES SPORT DE YAOUNDE

We have the honor to inform you that the Interprofessional Organization for the Development of Aquaculture in Cameroon (OIDAC) under the supervision of the Ministry of Livestock, Fisheries and Animal Industries (MINEPIA), is organizing the first edition of the "Cameroon Interprofessional Aquaculture Fair (SIAC2024).

Date : from December 2 to 7, 2024
Place : Palais Polyvalent des Sport of Yaoundé

For any information please contact :
Interprofessional Organization for the Development of Aquaculture in Cameroon (OIDAC), Tel: +237 694 32 47 72 / 675 05 02 02 / email: contact@siac-cm.com / OIDAC24@gmail.com