



Exploring sustainable alternatives in aquaculture feeding: The role of insects

Rafaela Regina Fantatto^{a,b,*}, Joana Mota^{b,c,1}, Carolina Ligeiro^{a,d}, Inês Vieira^c, Leonardo Gaston Guilgur^{a,b}, Marisa Santos^{b,c,2}, Daniel Murta^{a,b,c,2}

^a *Ingredient Odissey SA – Entogreen, Santarém, Portugal*

^b *CiiEM – Centro de Investigação Interdisciplinar Egas Moniz, Portugal*

^c *Thunder Foods, Santarém, Portugal*

^d *Egas Moniz School of Health & Science, Portugal*

ARTICLE INFO

Keywords:

Sustainable aquaculture
Insects
Aquafeeds
Fish
Protein

ABSTRACT

The aquaculture sector faces uncertainty due to environmental changes, economic factors, and availability of food resources. Conventional aquatic feeds heavily depend on fishmeal. This results in sustainability challenges due to overexploitation of wild fish stocks, rising costs, and environmental impacts, which has driven the search for innovative and sustainable alternatives, such as insects. European Union legislation has evolved to allow the use of certain insect species in aquafeeds, favoring the market access and approval of additional species. However, regulations still need to be standardized across countries and the substrates approved for insect feed clearly defined, since the nutritional composition of insects depend on species and diet. These ingredients have high potential to replace fishmeal in aquatic feeds, although, present challenges regarding optimal growth and digestibility, specially due to the chitin in composition, that need to be overcome. However, chitin and its derivatives may also have positive effects in fish feeds as prebiotic and immunomodulator. 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. Based on the research available for this topic, this review aimed to evaluate the real potential of using insect-based raw-materials in feeds for aquaculture and their effects on growth, feed utilization, immunological response, disease resistance, quality, and safety of fish.

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

* Corresponding author.

E-mail address: rafaela.fantatto@entogreen.com (R.. Fantatto).

¹ These authors contributed equally to the paper

² These authors contributed equally to the paper

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. Aquaculture market

2.1. Global 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).

2.2. European market

Aquaculture production in the European Union (EU) increased by 11 % since 1990, but it declined by 8 % since 2018 (Gras et al., 2023). It represents approximately 1.0 % in volume and 1.5 % in value of global production. The production is mainly concentrated in four countries: Spain (24 %), France (21 %), Greece (11 %), and Italy (10 %), which collectively represent around 67 % of the total volume within the EU. France leads with 22 % of the total revenues, followed by Spain (15 %), Greece (15 %), and Italy (9 %), accounting for 61 % of the total revenues in the EU (Gras et al., 2023).

In 2020, the distribution of aquaculture production within the EU was as follows: marine fishes accounted for 23 % in weight, freshwater fishes contributed 27 %, and shellfish comprised the majority at 49 %. Regarding production value, marine fishes represented 45 %, freshwater fishes 27 %, and shellfish accounted for 28 %. The primary aquaculture species produced in 2020 were sea mussels, rainbow trout, blue mussels, Pacific cupped oysters, gilthead seabream, European seabass, common carp, and Atlantic bluefin tuna. These nine species collectively contributed to 87 % of the total EU aquaculture production in weight.

During 2020, the top high-value aquaculture species in the EU were rainbow trout, gilthead seabream, European seabass, Pacific cupped oysters, and Atlantic bluefin tuna. Together, these five species represented 64 % of the total value generated by aquaculture production in the EU (Gras et al., 2023).

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).

FMs 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 reevaluation 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 (Stadlander 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 domestica* (AD), *Grylodes 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, constraints persist regarding the substrate options on which insects can be reared, limited to raw materials also approved for other livestock species (Table 1). Overcoming these barriers requires revising current regulations to accommodate the needs and potential of the insect farming

Table 1

Current EU regulations concerning the feeding of insects and their use as feed.

Interesting substrates for insects (non-approved yet)	EU approved substrates for insects	Some EU approved insect species	Use in animal feeds
Pre-consumer and post-consumer catering waste	Vegetal origin	<i>Hermetia illucens</i>	Pet animals ^a
Former foodstuffs containing fish or meat	Dairy and egg	<i>Musca domestica</i>	Fur and other animals
Manure	Rendered fats	<i>Tenebrio molitor</i>	Aquaculture
Slaughterhouse side streams	Collagen, gelatine, honey	<i>Acheta domestica</i> <i>Grylodes sigillatus</i> and <i>Gryllus assimilis</i>	Poultry Pig

^aPet insectivores can be fed with live insects

sector.

Clear and unambiguous regulation will level the playing field, encourage investments, add trust, and standardize the industry (van der Spiegel, 2016). The primary objective for each government in regulating insect food and feed production will be to ensure product safety and quality.

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 (Table 2 and 3). 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 2

Main nutritional components (%) of three insect species, soybean meal and fishmeal^a.

Nutritional Constituents	Species			Soymeal	Fishmeal (FM)
	<i>Hermetia illucens</i> larvae (HIL)	<i>Musca domestica</i> maggot meal (MDM meal)	<i>Tenebrio molitor</i> (TM)		
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

^aData are derived from published papers (Amza and Tamiru, 2017; Howlader et al., 2023; Makkar et al., 2014; Tran et al., 2015; Yu et al., 2023).

Table 3
Amino acid composition (g/16 g nitrogen) of insect meals, soybean meal and fishmeal^a.

Nutritional Constituents		Species				
		<i>Hermetia illucens</i> larvae (HIL)	<i>Musca domestica</i> maggot meal (MDM meal)	<i>Tenebrio molitor</i> (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
	Non-essential amino acids	Alanine	7.7	5.8	7.3	4.5
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

^aData are derived from published papers (Amza and Tamiru, 2017; Howlader et al., 2023; Makkar et al., 2014; Tran et al., 2015; Yu et al., 2023).

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 (Malemajta 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; Zarantonello 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

6.1. 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*, *Grylloides 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).

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

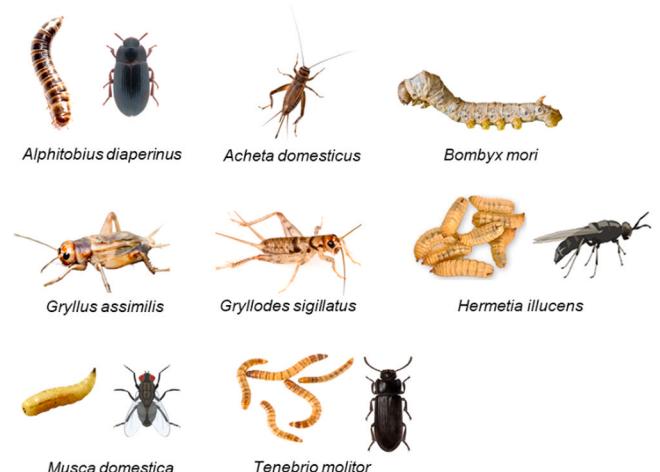


Fig. 1. Eight important insect species for replacing fish meals in aquafeed.



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

meal supplementation in various fish species have shown positive impacts on growth performance and feed consumption, among other advantages showed in Table 4. Research demonstrates the potential to enhance the cardioprotective characteristics of fish fillets through tailored insect fatty acid profiles, further emphasising the versatility 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; Stadlander 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, such as those shown in Table 5, revealing that the percentage of dietary inclusion hinges on factors such as feeding habits and farming conditions (Terova et al., 2021). 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

Table 4
Feeding trials with *Hermetia illucens* larvae (HIL) as a replacement for fishmeal in aquafeed.

Fish species and type of dietary habit	Duration of trial	Form of presentation	HIL inclusion in the diets (g/kg diet)	FM replacement (%)	Main results	References
Jian carp (<i>Cyprinus carpio</i>) Omnivorous	59 days	Defatted HIL meal	0, 2.6, 5.3, 7.6, 10.6	0, 25, 50, 75, 100	All diets were consumed equally, suggesting no impact on voluntary feed intake with defatted HIL meal. No significant effects on fish growth were observed across the tested diets. At 75 % FM replacement, dietary stress and intestinal histopathological damage were noted.	(S. Li et al., 2017)
Juvenile Yellow Catfish (<i>Pelteobagrus fulvidraco</i>) Carnivorous	8 weeks	HIL meal	0, 56, 85, 113, 141, 169	0, 10, 15, 20, 25, 30	Replacing up to 20 % of FM with HIL meal in the yellow catfish diet did not negatively impact growth performance, including weight gain, FCR, and body/muscle composition. This corresponds to about 8.9 % of the total CP in the diet, with no significant changes observed in other parameters like dry matter, CP, crude lipids, gross energy, and ADCs.	(Hu et al., 2017)
Rainbow trout (<i>Oncorhynchus mykiss</i>) Carnivorous	78 days	Partially defatted HIL meal	0, 200, 400	0, 25, 50	Partially defatted HIL meal can replace up to 50 % of FM in rainbow trout diets (400 g/kg) with no adverse effects on growth, condition factor, somatic indexes, and gut morphology. In fillet composition, including up to 200 g/kg of partially defatted HIL meal has no negative impact on long-chain FAs (EPA and DHA).	(Renna et al., 2017)
	7 weeks	Defatted HIL Meal	0, 280	0, 46	No significant differences were found in fish growth, feed conversion, or meat quality. However, protein utilization decreased in the diet containing 280 g/kg of defatted HIL meal.	(Stadlander et al., 2017)
Atlantic salmon (<i>Salmo salar</i> L.) Carnivorous	16 weeks	HIL meal	0, 49.1, 98.4, 98.4, 147.5	0, 33, 66, 100	Substituting 100 % of FM had no impact on fillet quality. Salmon fed with HIL meal showed increased neutral n-3 PUFA in fillets. Consumer tests indicated uniform positive reception across all dietary groups.	(Bruni et al., 2020)
European sea bass (<i>Dicentrarchus labrax</i>) Carnivorous	8 weeks	Dry HIL meal	0, 72., 101, 148	0, 25, 35, 50	Replacing FM with dry HIL meal in European seabass diets is generally feasible without adversely affecting fish health or growth performance.	(Abdel-Tawwab et al., 2020)
	62 days	HIL meal	0, 65, 130, 195	0, 15, 30, 45	Substituting 45 % of FM with HIL meal (195 g/kg diet) in juvenile European seabass diets has no adverse effects on color, liver health, fillet fatty acid profile, and quality indexes. HIL meal may also contribute to lowering liver and fillet lipid oxidation.	(Moutinho et al., 2021)

HIL = *Hermetia illucens* larvae; FM = Fish meal; FCR = Feed conversion ratio; CP = Crude protein; ADC = Apparent digestibility coefficient; FA = Fatty acids; EPA = Eicosapentaenoic acid; DHA = Docosahexaenoic acid; PUFA = polyunsaturated fatty acids

Table 5
Feeding trials with *Tenebrio molitor* as a replacement for fishmeal in aquafeed.

Fish species and type of dietary habit	Duration of trial	Form of presentation	TM inclusion in the diets (g/kg diet)	FM replacement (%)	Main results	References
African catfish (<i>Clarias gariepinus</i>) Omnivorous	7 weeks	TM meal	0, 86.8, 173.5260.3, 347.0, 433.8	0, 20, 40, 60, 80, 100	FM can be replaced with TM meal up to 40 % (173.5 g/kg) without significant differences from the control diet. Even at 80 % replacement (347 g/kg), fish maintain good growth and feed utilization performance.	(Ng et al., 2001)
Common catfish fingerlings (<i>Ameiurus melas</i>) Omnivorous	90 days	TM meal	0, 119.2	0, 50	A diet replacing 50 % of FM with TM sustained catfish fingerlings' growth, but FM-only feed outperformed TM meal feed.	(Roncarati et al., 2015)
Rainbow trout (<i>Oncorhynchus mykiss</i>) Omnivorous	8 weeks	TM meal	0, 70, 140, 210, 280	0, 10, 20, 30, 40	Weight gain and specific growth rate significantly increased with up to 140 g/kg of TM meal in the diet, but decreased with 280 g/kg of TM meal. Diets with TM meal resulted in higher protein efficiency ratio and lower FCR compared to the control with no TM meal. This study recommends including at least 280 g/kg TM meal in rainbow trout diets, as it does not compromise growth, nutrient composition, or fish health. Optimal performance was observed at 140 g/kg, surpassing the control diet with fish meal.	(Jeong et al., 2020)
	90 days	TM meal	0, 250, 500	0, 35, 67	Fish fed 250 g/kg TM meal exhibited higher body weight, though not statistically significant compared to the control group. Increasing TM meal in the diet decreased HIS, indicating a positive impact on fish health. Inclusion of TM meal in rainbow trout aquafeed did not significantly affect relevant quality parameters in fish and fillets.	(Iaconisi et al., 2018)
Yellow catfish juvenile (<i>Pelteobagrus fulvidraco</i>) Carnivorous	5 weeks	TM meal	0, 90, 180, 270	0, 25, 50, 75	Incorporating TM meal in catfish diet had no negative impact on growth performance. The 75 % replacement group (270 g/kg) showed significantly higher survival rates than the control, similar to the 50 % replacement group (180 g/kg). Additionally, inclusion of 180 g/kg enhanced immune response and bacterial resistance. These results indicate that TM meal supplementation has potential to boost both innate and adaptive immune responses in catfish.	(Su et al., 2017)
European sea bass (<i>Dicentrarchus labrax</i>) Carnivorous	10 weeks	Defatted TM meal	0, 180, 360, 600	0, 40, 80, 100	Up to 80 % defatted TM meal (360 g/kg) had no impact on protein and lipid digestibility. Growth performance and muscle levels of EPA, DHA, and long-chain FAs remained consistent. It is feasible to substitute FM with 80 % defatted TM meal in European seabass diets without affecting feed intake and central homeostatic regulation.	(Basto, Calduch-Giner, et al., 2021)

TM = *Tenebrio molitor*; FM = Fish meal; HIS = Hepatosomatic Index; FCR = Feed conversion ratio; FA = Fatty acids; EPA = Eicosapentaenoic acid; DHA = Docosahexaenoic acid

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. The examination of studies involving carnivorous fish, such as rainbow trout and European seabass, indicates promising results regarding the substitution of FM with TM meals. In the case of the rainbow trout, the inclusion of mealworms in the diet demonstrated positive effects on growth performance, protein efficiency ratio, and feed conversion ratio, with optimal performance observed (Jeong et al., 2020). Similarly, European seabass exhibited consistent growth performance with the inclusion of defatted TM meal in the diet, demonstrating the possibility of replacing FM with

80 % defatted TM meal without affecting feed intake and central homeostatic regulation (Basto et al., 2021).

For omnivorous fish species such as African catfish (*Clarias gariepinus*), common catfish (*Ameiurus melas*), and yellow catfish (*Pelteobagrus fulvidraco*), studies reveal positive outcomes in FM replacement with TM meal. Studies performed in African catfish demonstrated that the replacement of FM with TM meal is viable, with good growth and feed utilization, even up to 80 % substitution (Ng et al., 2001). Common catfish fingerlings exhibited sustained growth with 50 % replacement of fish meal with mealworms, although slightly inferior to the control group (Roncarati et al., 2015). In the case of yellow catfish juveniles, the inclusion of TM meal in the diet did not adversely affect growth performance, highlighting potential immune response improvements with mealworm supplementation (Su et al., 2017). These results collectively position mealworms as a promising and sustainable alternative protein source for both carnivorous and omnivorous fish, paving the way for further research and implementation in aquaculture practices. However, addressing critical knowledge gaps, unravelling molecular mechanism, and exploring the nutritional potential of mealworms in specific aquaculture applications remains imperative for ensuring the successful integration of this novel protein source into aquaculture practices (Alfiko et al., 2022; Roncarati et al., 2015; Terova et al., 2021).

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. Some of these studies are shown in Table 6. 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. 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).

Studies focusing on carnivorous fish, particularly barramundi (*Lates calcarifer*), have explored the potential of MDM meal as a substitute for FM in aquafeeds (Lin and Mui, 2017). Over an 8-week trial period, MDM meal was included in varying proportions, and results indicated no significant differences in various parameters tested among the different dietary groups tested. While fish fed diets with higher MDM meal content exhibited lower condition factors, there were no noticeable variations in whole body moisture, crude protein and lipid across all dietary treatments. This suggests that replacing FM with MDM meal up to a certain level did not negatively impact the growth and feed utilization of barramundi (Lin and Mui, 2017). Feeding trials spanning 10 weeks and 56 days for African catfish (*Clarias gariepinus*) and Nile tilapia (*Oreochromis niloticus*) respectively, investigated the suitability of MDM meal as a partial replacement for FM (Kolawole et al., 2018; Ogunji et al., 2008). In African catfish, the inclusion of MDM meal demonstrated positive effects on growth performance. For Nile tilapia, despite apparent digestibility coefficients for dietary matter and crude lipids remaining similar across feeding groups, a decrease in crude protein digestibility was noted at higher MDM meal inclusion levels. Overall, the studies endorse the potential of MDM meal as a sustainable protein

source for both carnivorous and omnivorous fish and understand species-specific responses (Kolawole et al., 2018; Ogunji et al., 2008).

In a broader context, the cumulative findings from these 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, as outlined in Table 2.

These three insect species exhibit a substantial crude protein (CP) level ranging from 42.1 % to 60.7 % as indicating in Table 2. Although, this level of CP is lower than that found in FM, but is similar to soybean

Table 6
Feeding trials with *Musca domestica* (MD) as a replacement for fishmeal in aquafeed.

Fish species and type of dietary habit	Duration of trial	Form of presentation	MDM inclusion in the diets (g/kg diet)	FM replacement (%)	Main results	References
African catfish (<i>Clarias gariepinus</i>) Omnivorous	10 weeks	MDM meal	0, 97.7, 153.8, 213.9, 355.0, 437.4, 529.6	0, 20, 30, 40, 50,60, 70,80	Fish fed with 70 % MDM meal had the highest weight gain (437.4 g/kg). Specific and relative growth rates were significantly elevated with a 60 % MDM meal diet (355 g/kg), whereas the lowest rates were observed in fish fed 20 % MDM meal and the control diet. These results indicate the effective utilization of MDM meal as a partial fish meal replacement for African catfish, supporting growth and nutritional benefits.	(Kolawole et al., 2018)
Nile tilapia (<i>Oreochromis niloticus</i>) Omnivorous	56 days	MDM meal	0, 150, 300	0, 17, 37	Similar digestibility coefficients were observed for dietary matter and crude lipids across feeding groups, indicating excellent growth performance and health in Nile tilapia. The use of MDM meal in fingerling diets is endorsed, but a decline in CP digestibility was noted at 300 g/kg inclusion.	(Ogunji et al., 2008)
Barramundi (<i>Lates calcarifer</i>) Carnivorous	8 weeks	MDM meal	0, 100, 150, 200, 300	0, 25, 38, 51, 76	No significant differences were observed in final weight, weight gain, feed intake, feed efficiency, protein efficiency ratio, and survival among the tested dietary groups. Fish fed diets with 200 and 300 g/kg of MDM meal exhibited lower condition factors compared to those on the diet with 150 g/kg of MDM meal and the fish meal control diet. However, whole body moisture, crude protein (CP), and lipid content showed no variations across all dietary treatments. These findings indicate that replacing up to 300 g/kg of MDM meal for fish meal does not adversely impact the growth and feed utilization of barramundi.	(Lin and Mui, 2017)

MDM = *Musca domestica* maggot; FM = Fish meal; CP = crude prote

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 3 (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 3), 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 2). 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 (Stadlander 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 \rightarrow 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, Abdel-Razik, 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, Gewaily, 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) (Fines and Holt, 2010), channel rockcod (*Sebastes 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.

Rimoldi et al. (2023) evaluated the prebiotic effect of including 1.6 % of HI pupal exuviae in the diet of rainbow trout (*Oncorhynchus mykiss*). The results indicated an increase in chitinolytic intestinal bacteria abundance and modulation of the intestinal microbiota, resulting in a higher quantity of short-chain fatty acids (SCFAs) in the intestine. Chitinolytic enzymes, classified as endo-chitinases and exo-chitinases (chitobiosidases and glucosaminidases), play a significant role.

Studies conducted by Eggink et al. (2022) demonstrated that chitin can act as a source of nutrients and antinutrients, depending on its inclusion in the diet, both in Nile tilapia (*Oreochromis niloticus*) and rainbow trout (*Oncorhynchus mykiss*).

In other species such as common carp (*Cyprinus carpio*), it was observed that supplementing with 1 % chitin for 90 days resulted in a significantly lower final body weight compared to no supplemented diets (Gopalakannan and Arul, 2006), demonstrating that different species may exhibit different behaviors in response to 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).

In feeding Atlantic salmon, it was found that a complete replacement of FM with HIL meal did not affect the quality of the fillets. Specifically, neutral n-3 PUFA (polyunsaturated fatty acids) significantly increased in Atlantic salmon fillets fed HIL meal diets; it was also observed that diets with different amounts of HIL meal had no effect on volatile organic composition (Bruni et al., 2020). Other studies with *Salmo salar* in graded amounts of HIL flour evaluated digestibility and the effect on growth and fillet (Weththasinghe et al., 2021). Up to 12.5 % insect meal supported high growth performance, however, reduced digestibility and protein efficiency. In juvenile European seabass, the digestibility of HI and TM nutrients demonstrates that TM flour is the most promising alternative to FM in diets for this fish species as it has the highest content of digestible protein (641 mg/g DM) and essential digestible amino acids (296 mg/g DM) (Basto et al., 2020). The inclusion of TM also did not change feed intake and its regulatory mechanisms in European seabass (Basto et al., 2022; Basto et al., 2021). However, when TM was included at high levels (as a total replacement for FM) in seabass diets, it induced changes in liver and plasma metabolites, suggesting changes in the fish's intermediary metabolism that may compromise growth performance and/or long-term fish health status (Basto et al., 2022). The literature highlights impressive results in growth performance when different fish species are fed insects. For several fish species, HIL meal has been successfully incorporated as a feed ingredient, including Atlantic salmon (*Salmo salar*) (10–20 % dietary inclusion), Nile tilapia (*Oreochromis niloticus*) (1–10 % of dietary inclusion), and rainbow trout (*Oncorhynchus mykiss*) (20 %–40 % dietary inclusion) (Belghit et al., 2019; Fisher et al., 2020; Tippayadara et al., 2021). However, other studies have found that growth performance was suppressed with dietary inclusion of HIL meal, including turbot (*Psetta maxima*) (16.5 %–75.6 % dietary inclusion) and rainbow trout (6.6 %–26.4 % dietary inclusion) (Dumas et al., 2018; Kroeckel et al., 2012). These seemingly contradictory results may be due to differences in HIL meal inclusion levels, substituted protein sources, and HIL meal quality (Hua, 2021; Liland et al., 2021; Weththasinghe et al., 2021). The quality of HIL meal depends, among other factors, on processing procedures, protein content, amino acid profile, and chitin content. Some studies have hypothesized that chitin could have a potential negative impact on fish performance and nutrient digestibility (Eggink et al., 2022). However, studies conducted with tilapia and salmon carp (*Aristichthys nobilis*) fed BSF (Kroeckel et al., 2012; St-Hilaire et al., 2007; Chen et al., 2023) show a significant increase in weight gain and growth rate. The direct relationship between the inclusion of insects in the diet and improved

zootechnical performance is evident, highlighting the potential of this practice in different aquacultural contexts. Furthermore, studies emphasize the influence of the inclusion of insects on the quality of meat and the general health of fish, providing improvements in texture, flavor, and nutritional value of meat, in addition to strengthening the immune system and reducing susceptibility to diseases (Wang et al., 2021).

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. As the insect sector continues to expand, the accessibility of the raw materials linked to these organisms is anticipated to increase, therefore enhancing their utilization. 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.

An unpublished study conducted a mixture of black soldier fly (HI) and mealworm (TM) protein, which, to our knowledge, is the first insect protein mix incorporated into aquafeed, and its impact was evaluated on salmon and seabass.

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.

Funding

This work was funded by Thunder Foods S.A.

Institutional review board statement

Not applicable. Informed Consent Statement: Not applicable.

Acknowledgments

This work was supported by Iceland, Liechtenstein and Norway through EEA Grants 2014-2021, InFishMix Project (PT-INNOVATION-0094).

CRediT authorship contribution statement

Daniel Murta: Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Marisa Santos:** Writing – review & editing, Supervision, Project administration. **Leonardo Guilgur:** Writing – review & editing, Visualization, Conceptualization. **Ines Vieira:** Writing – review & editing, Writing – original draft, Investigation. **Carolina Ligeiro:** Writing – original draft, Investigation. **Joana Mota:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Rafaela Regina Fantatto:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

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

Data availability

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

References

- Abdel-Ghany, H.M., Salem, M.E., 2020. Effects of dietary chitosan supplementation on farmed fish; a review. *Rev. Aquac.* 12 (1), 438–452. <https://doi.org/10.1111/raq.12326>.
- Abdel-Tawwab, M., Khalil, R.H., Metwally, A.A., Shakweer, M.S., Khallaf, M.A., Abdel-Latif, H.M.R., 2020. Effects of black soldier fly (*Hermetia illucens* L.) larvae meal on growth performance, organs-somatic indices, body composition, and hemato-biochemical variables of European seabass, *Dicentrarchus labrax*. *Aquaculture* 522, 735136. <https://doi.org/10.1016/j.aquaculture.2020.735136>.
- Ahmed, F., Soliman, F.M., Adly, M.A., Soliman, H.A.M., El-Matbouli, M., Saleh, M., 2021. Dietary Chitosan Nanoparticles: potential role in modulation of rainbow trout (*Oncorhynchus mykiss*) Antibacterial defense and intestinal immunity against enteric redmouth disease. *Mar. Drugs* 19 (2), 72. <https://doi.org/10.3390/md19020072>.
- Alegbeleye, W.O., Obasa, S.O., Olude, O.O., Otubu, K., Jimoh, W., 2012. Preliminary evaluation of the nutritive value of the variegated grasshopper (*Zonocerus variegatus* L.) for African catfish *Clarias gariepinus* (Burchell, 1822) fingerlings. *Aquac. Res.* 43 (3), 412–420. <https://doi.org/10.1111/J.1365-2109.2011.02844.X>.
- Alfiko, Y., Xie, D., Astuti, R.T., Wong, J., Wang, L., 2022. Insects as a feed ingredient for fish culture: status and trends. *Aquac. Fish.* 7 (2), 166–178. <https://doi.org/10.1016/J.AAF.2021.10.004>.
- Allegritti, G., Schmidt, V., Talamini, E., 2017. Insects as feed: species selection and their potential use in Brazilian poultry production. *World's Poult. Sci. J.* 73 (4), 928–937. <https://doi.org/10.1017/S004393391700054X>.
- Allegritti, G., Talamini, E., Schmidt, V., Bogorni, P.C., Ortega, E., 2018. Insect as feed: an energy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. *J. Clean. Prod.* 171, 403–412. <https://doi.org/10.1016/j.jclepro.2017.09.244>.
- Amza, N., Tamiru, M., 2017. Insects as an option to conventional protein sources in animal feed: A review paper. *Global Journal of Science Frontier Research: D Agriculture and Veterinary* 17 (2).
- Aragão, C., Gonçalves, A.T., Costas, B., Azeredo, R., Xavier, M.J., Engrola, S., 2022. Alternative proteins for fish diets: implications beyond growth. *Animals* 12 (9), 1211. <https://doi.org/10.3390/ANI12091211>.
- Astorg, P., Arnault, N., Czernichow, S., Noisette, N., Galan, P., Hercberg, S., 2004. Dietary intakes and food sources of n-6 and n-3 PUFA in french adult men and women. *Lipids* 39 (6), 527–535. <https://doi.org/10.1007/S11745-004-1259-6>.
- Barros-Cordeiro, K.B., Bão, S.N., Pujol-Luz, J.R., 2014. Intra-puparial development of the black soldier-fly, *Hermetia illucens*, 14 (83), 1–10. <https://doi.org/10.1673/031.014.83>.
- Barroso, F.G., de Haro, C., Sánchez-Muros, M.J., Venegas, E., Martínez-Sánchez, A., Pérez-Bañón, C., 2014. The potential of various insect species for use as food for fish. *Aquaculture* 422–423, 193–201. <https://doi.org/10.1016/J.AQUACULTURE.2013.12.024>.
- Barroso, F.G., Sánchez-Muros, M.J., Rincón, M.Á., Rodríguez-Rodríguez, M., Fabrikov, D., Morote, E., Guil-Guerrero, J.L., 2019. Production of n-3-rich insects by bioaccumulation of fishery waste. *J. Food Compos. Anal.* 82, 103237. <https://doi.org/10.1016/J.JFCA.2019.103237>.
- Basto, A., Caldusch-Giner, J., Oliveira, B., Petit, L., Sá, T., Maia, M.R.G., Fonseca, S.C., Matos, E., Pérez-Sánchez, J., Valente, L.M.P., 2021. The use of defatted tenebrio molitor larvae meal as a main protein source is supported in European Sea Bass (*Dicentrarchus labrax*) by data on growth performance, lipid metabolism, and flesh quality. *Front. Physiol.* 12. <https://doi.org/10.3389/fphys.2021.659567>.
- Basto, A., Matos, E., Valente, L.M.P., 2020. Nutritional value of different insect larvae meals as protein sources for European seabass (*Dicentrarchus labrax*) juveniles. *Aquaculture* 521, 735085. <https://doi.org/10.1016/J.AQUACULTURE.2020.735085>.
- Basto, A., Valente, L.M.P., Conde-Sieira, M., Soengas, J.L., 2021. Central regulation of food intake is not affected by inclusion of defatted *Tenebrio molitor* larvae meal in diets for European seabass (*Dicentrarchus labrax*). *Aquaculture* 544. <https://doi.org/10.1016/j.aquaculture.2021.737088>.
- Basto, A., Valente, L.M.P., Soengas, J.L., Conde-Sieira, M., 2022. Partial and total fishmeal replacement by defatted *Tenebrio molitor* larvae meal do not alter short- and mid-term regulation of food intake in European sea bass (*Dicentrarchus labrax*). *Aquaculture* 560, 738604. <https://doi.org/10.1016/J.AQUACULTURE.2022.738604>.
- Belforti, M., Gai, F., Lussiana, C., Renna, M., Malfatto, V., Rotolo, L., De Marco, M., Dabbou, S., Schiavone, A., Zoccarato, I., Gasco, L., 2015. Tenebrio molitor Meal in Rainbow Trout (*Oncorhynchus mykiss*) Diets: effects on animal performance, nutrient digestibility and chemical composition of filets. *Ital. J. Anim. Sci.* 14 (4), 670–676. <https://doi.org/10.4081/IJAS.2015.4170>.
- Belghit, I., Liland, N.S., Gjesdal, P., Biancarosa, I., Menchetti, E., Li, Y., Waagbø, R., Krogdahl, Å., Lock, E.J., 2019. Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (*Salmo salar*). *Aquaculture* 503, 609–619. <https://doi.org/10.1016/J.AQUACULTURE.2018.12.032>.
- Borrelli, L., Varriale, L., Dipinetto, L., Pace, A., Menna, L.F., Fioretti, A., 2021. Insect derived lauric acid as promising alternative strategy to antibiotics in the antimicrobial resistance scenario. *Front. Microbiol.* 12, 620798. <https://doi.org/10.3389/FMICB.2021.620798/BIBTEX>.
- Bruni, L., Belghit, I., Lock, E.J., Secci, G., Taiti, C., Parisi, G., 2020. Total replacement of dietary fish meal with black soldier fly (*Hermetia illucens*) larvae does not impair physical, chemical or volatile composition of farmed Atlantic salmon (*Salmo salar* L.). *J. Sci. Food Agric.* 100 (3), 1038–1047. <https://doi.org/10.1002/JFSA.10108>.
- Calder, P.C., 2008. Polyunsaturated fatty acids, inflammatory processes and inflammatory bowel diseases. *Mol. Nutr. Food Res.* 52 (8), 885–897. <https://doi.org/10.1002/MNFR.200700289>.
- Chemello, G., Renna, M., Caimi, C., Guerreiro, I., Oliva-Teles, A., Enes, P., Biasato, I., Schiavone, A., Gai, F., Gasco, L., 2020. Partially defatted *Tenebrio molitor* larva meal in diets for grow-out rainbow trout, *Oncorhynchus mykiss* (Walbaum): effects on growth performance, diet digestibility and metabolic responses, 2020, Vol. 10, 229 *Animals* 10 (2), 229. <https://doi.org/10.3390/ANI10020229>.
- Chen, M., Wang, L., Zheng, C., Ma, A., Hu, K., Xiang, A., Sun, Z., Xie, B., Xiong, G., Shi, L., Chen, S., Wu, W., 2023. Novel ACE inhibitory peptides derived from bighead carp (*Aristichthys nobilis*) hydrolysates: screening, inhibition mechanisms and the bioconjugation effect with graphene oxide. *Food Biosci.* 52, 102399. <https://doi.org/10.1016/J.FBIO.2023.102399>.
- Čičková, H., Newton, G.L., Lacy, R.C., Kozánek, M., 2015. The use of fly larvae for organic waste treatment. In: *In Waste Management*, Vol. 35. Elsevier Ltd, pp. 68–80. <https://doi.org/10.1016/j.wasman.2014.09.026>.
- Daniel, N., 2018. A review on replacing fish meal in aqua feeds using plant protein sources. *Int J Fish Aquat* 6 (2), 164–179. <https://www.fisheriesjournal.com/archives/2018/vol6issue2/PartC/6-1-35-823.pdf>.
- Danulat, E., 1986. The effects of various diets on chitinase and β -glucosidase activities and the condition of cod, *Gadus morhua* (L.). *J. Fish. Biol.* 28 (2), 191–197. <https://doi.org/10.1111/j.1095-8649.1986.tb05157.x>.
- Dawood, M.A.O., Abdel-Razik, N.I., Gewaily, M.S., Sewilam, H., Paray, B.A., Soliman, A.A., Abdelhcie, E.Y., Aboubakr, M., Van Doan, H., El-Sabagh, M., El Basuini, M.F., 2020. β -Glucan improved the immunity, hepato-renal, and histopathology disorders induced by chlorpyrifos in Nile tilapia. *Aquac. Rep.* 18, 100549. <https://doi.org/10.1016/j.aqrep.2020.100549>.
- Dawood, M.A.O., Gewaily, M.S., Soliman, A.A., Shukry, M., Amer, A.A., Younis, E.M., Abdel-Warith, A.-W.A., Van Doan, H., Saad, A.H., Aboubakr, M., Abdel-Latif, H.M.R., Fadl, S.E., 2020. Marine-derived chitosan nanoparticles improved the intestinal histo-morphometrical features in association with the health and immune response of grey mullet (*Liza ramada*). *Mar. Drugs* 18 (12), 611. <https://doi.org/10.3390/md18120611>.
- De Souza-Vilela, J., Andrew, N.R., Ruhnke, I., 2019. Insect protein in animal nutrition. *Anim. Prod. Sci.* 59 (11), 2029–2036. <https://doi.org/10.1071/AN19255>.
- Dumas, A., Raggi, T., Barkhouse, J., Lewis, E., Weltzien, E., 2018. The oil fraction and partially defatted meal of black soldier fly larvae (*Hermetia illucens*) affect differently growth performance, feed efficiency, nutrient deposition, blood glucose and lipid digestibility of rainbow trout (*Oncorhynchus mykiss*). *Aquaculture* 492, 24–34. <https://doi.org/10.1016/J.AQUACULTURE.2018.03.038>.
- Dyall, S.C., Michael, G.J., Michael-Titus, A.T., 2010. Omega-3 fatty acids reverse age-related decreases in nuclear receptors and increase neurogenesis in old rats. *Int. J. Osteopath. Med.* 13 (3), 108. <https://doi.org/10.1016/j.ijosm.2010.07.008>.
- Eggink, K.M., Pedersen, P.B., Lund, I., Dalsgaard, J., 2022. Chitin digestibility and intestinal exochitinase activity in Nile tilapia and rainbow trout fed different black

- soldier fly larvae meal size fractions. *Aquac. Res.* 53 (16), 5536–5546. <https://doi.org/10.1111/are.16035>.
- Engle, C.R., van Senten, J., 2022. Resilience of communities and sustainable aquaculture: governance and regulatory effects. *Fishes* 7 (5), 268. <https://doi.org/10.3390/FISHES7050268>.
- Esteban, M.A., Cuesta, A., Ortuño, J., Meseguer, J., 2001. Immunomodulatory effects of dietary intake of chitin on *Gilthead seabream* (L.) innate immune system. *Fish. Shellfish Immunol.* 11 (4), 303–315. <https://doi.org/10.1006/fsim.2000.0315>.
- FAO, 2022. The state of world fisheries and aquaculture 2022. State World Fish. *Aquac.* 2022 <https://doi.org/10.4060/CC0461EN>.
- Fawole, F.J., Adeoye, A.A., Tiamiyu, L.O., Ajala, K.I., Obadara, S.O., Ganiyu, I.O., 2020. Substituting fishmeal with *Hermetia illucens* in the diets of African catfish (*Clarias gariepinus*): effects on growth, nutrient utilization, haemato-physiological response, and oxidative stress biomarker. *Aquaculture* 518. <https://doi.org/10.1016/j.aquaculture.2019.734849>.
- Fetterman, J.W., Zdanowicz, M.M., 2009. Therapeutic potential of n-3 polyunsaturated fatty acids in disease. *Am. J. Health-Syst. Pharm.* 66 (13), 1169–1179. <https://doi.org/10.2146/AJHP080411>.
- Figueras, M., Oliván, M., Busquets, S., López-Soriano, F.J., Argilés, J.M., 2011. Effects of Eicosapentaenoic Acid (EPA) treatment on insulin sensitivity in an animal model of diabetes: improvement of the inflammatory status. *Obesity* 19 (2), 362–369. <https://doi.org/10.1038/OBY.2010.194>.
- Fines, B.C., Holt, G.J., 2010. Chitinase and apparent digestibility of chitin in the digestive tract of juvenile coho, *Rachycentron canadum*. *Aquaculture* 303 (1–4), 34–39. <https://doi.org/10.1016/j.aquaculture.2010.03.010>.
- Fisher, H.J., Collins, S.A., Hanson, C., Mason, B., Colombo, S.M., Anderson, D.M., 2020. Black soldier fly larvae meal as a protein source in low fish meal diets for Atlantic salmon (*Salmo salar*). *Aquaculture* 521, 734978. <https://doi.org/10.1016/J.AQUACULTURE.2020.734978>.
- Gasco, L., Biancarosa, I., Liland, N.S., 2020. From waste to feed: a review of recent knowledge on insects as producers of protein and fat for animal feeds. *Curr. Opin. Green. Sustain. Chem.* 23, 67–79. <https://doi.org/10.1016/j.cogsc.2020.03.003>.
- Gasco, L., Biasato, I., Dabbou, S., Schiavone, A., Gai, F., 2019. Animals fed insect-based diets: state-of-the-art on digestibility, performance and product quality. *Animals* 9 (4), 170. <https://doi.org/10.3390/ANI9040170>.
- Gasco, L., Gai, F., Maricchiolo, G., Genovese, L., Ragonese, S., Bottari, T., Caruso, G., 2018. Fishmeal Altern. Protein Sources *Aquac. Feeds* 1–28. https://doi.org/10.1007/978-3-319-77941-6_1.
- Gasco, L., Henry, M., Piccolo, G., Marono, S., Gai, F., Renna, M., Lussiana, C., Antonopoulou, E., Mola, P., Chatzifotis, S., 2016. *Tenebrio molitor* meal in diets for European sea bass (*Dicentrarchus labrax* L.) juveniles: growth performance, whole body composition and in vivo apparent digestibility. *Anim. Feed Sci. Technol.* 220, 34–45. <https://doi.org/10.1016/J.ANIFEEDSCI.2016.07.003>.
- Gaudio, G., Marzorati, G., Faccenda, F., Weil, T., Lunelli, F., Cardinaletti, G., Marino, G., Olivotto, L., Parisi, G., Tibaldi, E., Tuohy, K.M., Fava, F., 2021. Processed animal proteins from insect and poultry by-products in a fish meal-free diet for rainbow trout: impact on intestinal microbiota and inflammatory markers. *Int. J. Mol. Sci.* 22 (11), 5454. <https://doi.org/10.3390/ijms22115454>.
- Gopalakannan, A., Arul, V., 2006. Immunomodulatory effects of dietary intake of chitin, chitosan and levamisole on the immune system of *Cyprinus carpio* and control of *Aeromonas hydrophila* infection in ponds. *Aquaculture* 255 (1–4), 179–187. <https://doi.org/10.1016/j.aquaculture.2006.01.012>.
- Gras, M., Kupschus, S., Konrad, C., Pierucci, A., Hekim, Z., Vasilakopoulos, P., 2023. Scientific, technical and economic committee for fisheries (STECF), monitoring of the performance of the common fisheries policy (STECF-adhoc-23-01). *Publ. Off. Eur. Union.* <https://doi.org/10.2760/51391>.
- Gutowska, M.A., Drazen, J.C., Robison, B.H., 2004. Digestive chitinolytic activity in marine fishes of Monterey Bay, California. *Comp. Biochem. Physiol. Part A: Mol. Integr. Physiol.* 139 (3), 351–358. <https://doi.org/10.1016/j.cbpa.2004.09.020>.
- Hameed, A., Majeed, W., Naveed, M., Ramzan, U., Bordiga, M., Hameed, M., Ur Rehman, S., Rana, N., 2022. Success of aquaculture industry with new insights of using insects as feed. a review. *Fishes* 7 (6), 395. <https://doi.org/10.3390/fishes7060395>.
- Harris, J.W., 2007. Bees with varroa sensitive hygiene preferentially remove mite infested pupae aged \leq five days post capping. *J. Apic. Res.* 46 (3), 134–139. <https://doi.org/10.1080/00218839.2007.11101383>.
- Hashizume, A., Ido, A., Ohta, T., Thiaw, S.T., Morita, R., Nishikawa, M., Takahashi, T., Miura, C., Miura, T., 2019. Housefly (*Musca domestica*) larvae preparations after removing the hydrophobic fraction are effective alternatives to fish meal in aquaculture feed for red seabream (*Pagrus major*). *Fishes* 4 (3). doi, 3810.3390/fishes4030038.
- Hawkey, K.J., Lopez-Viso, C., Brameld, J.M., Parr, T., Salter, A.M., 2021. Insects: A Potential Source of Protein and Other Nutrients for Feed and Food. *Annu. Rev.* 9, 333–354. <https://doi.org/10.1146/ANNUREV-ANIMAL-021419-083930>.
- Henry, M.A., Gasco, L., Chatzifotis, S., Piccolo, G., 2018. Does dietary insect meal affect the fish immune system? The case of mealworm, *Tenebrio molitor* on European seabass, *Dicentrarchus labrax*. *Dev. Comp. Immunol.* 81, 204–209. <https://doi.org/10.1016/J.DCI.2017.12.002>.
- Henry, M., Gasco, L., Piccolo, G., Fountoulaki, E., 2015. Review on the use of insects in the diet of farmed fish: past and future. *Anim. Feed Sci. Technol.* 203 (1), 1–22. <https://doi.org/10.1016/J.ANIFEEDSCI.2015.03.001>.
- Howlader, S., Sumi, K.R., Sarkar, S., Billah, S.M., Ali, M.L., Howlader, J., Shahjahan, M., 2023. Effects of dietary replacement of fish meal by soybean meal on growth, feed utilization, and health condition of stinging catfish, *Heteropneustes fossilis*. *Saudi journal of biological sciences* 30 (3), 103601. <https://doi.org/10.1016/j.sjbs.2023.103601>.
- Hu, J., Wang, G., Huang, Y., Sun, Y., He, F., Zhao, H., Li, N., 2017. Effects of substitution of fish meal with black soldier fly (*Hermetia illucens*) larvae meal, in yellow catfish (*Pelteobagrus fulvidraco*) diets. *Isr. J. Aquac. - Bamidgheh.* 69. (<https://ija.scholasticahq.com/article/20879.pdf>).
- Hua, K., 2021. A meta-analysis of the effects of replacing fish meals with insect meals on growth performance of fish. *Aquaculture* 530, 735732. <https://doi.org/10.1016/J.AQUACULTURE.2020.735732>.
- Iaconisi, V., Bonelli, A., Pupino, R., Gai, F., Parisi, G., 2018. Mealworm as dietary protein source for rainbow trout: body and fillet quality traits. *Aquaculture* 484, 197–204. <https://doi.org/10.1016/j.aquaculture.2017.11.034>.
- Iaconisi, V., Marono, S., Parisi, G., Gasco, L., Genovese, L., Maricchiolo, G., Bovera, F., Piccolo, G., 2017. Dietary inclusion of *Tenebrio molitor* larvae meal: Effects on growth performance and final quality traits of blackspot sea bream (*Pagellus bogaraveo*). *Aquaculture* 476, 49–58. <https://doi.org/10.1016/J.AQUACULTURE.2017.04.007>.
- Jeong, S.M., Khosravi, S., Mauliasari, I.R., Lee, S.M., 2020. Dietary inclusion of mealworm (*Tenebrio molitor*) meal as an alternative protein source in practical diets for rainbow trout (*Oncorhynchus mykiss*) fry. *Fish. Aquat. Sci.* 23 (1), 1–8. <https://doi.org/10.1186/S41240-020-00158-7/TABLES/7>.
- Jiménez-Gómez, C.P., Cecilia, J.A., 2020. Chitosan: a natural biopolymer with a wide and varied range of applications. *Molecules* 25 (17), 3981. <https://doi.org/10.3390/molecules25173981>.
- Kalupahana, N.S., Claycombe, K., Newman, S.J., Stewart, T., Siriwardhana, N., Matthan, N., Lichtenstein, A.H., Moustaid-Moussa, N., 2010. Eicosapentaenoic acid prevents and reverses insulin resistance in high-fat diet-induced obese mice via modulation of adipose tissue inflammation. *J. Nutr.* 140 (11), 1915–1922. <https://doi.org/10.3945/JN.110.125732>.
- Kolawole, A.A., Alda, A., Ugwumba, A., 2018. Economic evaluation of different culture enclosures for *Musca domestica* larval production and their utilization for *Clarias gariepinus* (Burchell, 1822) fingerlings diets. *Not. Sci. Biol.* 10 (4), 466–474. <https://doi.org/10.15835/NSB10410271>.
- Kono, M., Matsui, T., Shimizu, C., 1987. Effect of chitin, chitosan, and cellulose as diet supplements on the growth of cultured fish. *Nippon Suisan Gakkaishi* 53 (1), 125–129. <https://doi.org/10.2331/suisan.53.125>.
- Kroecel, S., Harjes, A.G.E., Roth, I., Katz, H., Wuertz, S., Susenbeth, A., Schulz, C., 2012. When a turbot catches a fly: evaluation of a pre-pupae meal of the Black Soldier Fly (*Hermetia illucens*) as fish meal substitute — Growth performance and chitin degradation in juvenile turbot (*Psetta maxima*). *Aquaculture* 364–365, 345–352. <https://doi.org/10.1016/J.AQUACULTURE.2012.08.041>.
- Kumar, V., Fawole, F.J., Romano, N., Hossain, M.S., Labh, S.N., Overturf, K., Small, B.C., 2021. Insect (black soldier fly, *Hermetia illucens*) meal supplementation prevents the soybean meal-induced intestinal enteritis in rainbow trout and health benefits of using insect oil. *Fish. Shellfish Immunol.* 109 <https://doi.org/10.1016/j.fsi.2020.12.008>.
- Lands, B., 2014. Historical perspectives on the impact of n-3 and n-6 nutrients on health. *Prog. Lipid Res.* 55 (1), 17–29. <https://doi.org/10.1016/J.PLIPRES.2014.04.002>.
- Leitzmann, M.F., Stampfer, M.J., Michaud, D.S., Augustsson, K., Colditz, G.C., Willett, W. C., Giovannucci, E.L., 2004. Dietary intake of n-3 and n-6 fatty acids and the risk of prostate cancer. *Am. J. Clin. Nutr.* 80 (1), 204–216. <https://doi.org/10.1093/AJCN/80.1.204>.
- Li, S., Ji, H., Zhang, B., Zhou, J., Yu, H., 2017. Defatted black soldier fly (*Hermetia illucens*) larvae meal in diets for juvenile Jian carp (*Cyprinus carpio* var. Jian): Growth performance, antioxidant enzyme activities, digestive enzyme activities, intestine and hepatopancreas histological structure. *Aquaculture* 477, 62–70. <https://doi.org/10.1016/J.AQUACULTURE.2017.04.015>.
- Liland, N.S., Araujo, P., Xu, X.X., Lock, E.J., Radhakrishnan, G., Prabhu, A.J.P., Belghit, I., 2021. A meta-analysis on the nutritional value of insects in aquafeeds. *J. Insects Food Feed* 7 (5), 743–759. <https://doi.org/10.3920/JIFF2020.0147>.
- Liland, N.S., Biancarosa, I., Araujo, P., Biemans, D., Bruckner, C.G., Waagbø, R., Torstensen, B.E., Lock, E.J., 2017. Modulation of nutrient composition of black soldier fly (*Hermetia illucens*) larvae by feeding seaweed-enriched media. *PLOS ONE* 12 (8), e0183188. <https://doi.org/10.1371/JOURNAL.PONE.0183188>.
- Lin, Y.H., Mui, J.J., 2017. Evaluation of dietary inclusion of housefly maggot (*Musca domestica*) meal on growth, fillet composition and physiological responses for barramundi, *Lates calcarifer*. *Aquac. Res.* 48 (5), 2478–2485. <https://doi.org/10.1111/ARE.13085>.
- Lu, C., Napier, J.A., Clemente, T.E., Cahoon, E.B., 2011. New frontiers in oilseed biotechnology: meeting the global demand for vegetable oils for food, feed, biofuel, and industrial applications. *Curr. Opin. Biotechnol.* 22 (2), 252–259. <https://doi.org/10.1016/J.COPBIO.2010.11.006>.
- Macusi, E.D., Cayacay, M.A., Borazon, E.Q., Sales, A.C., Habib, A., Fadli, N., Santos, M. D., 2023. Protein fishmeal replacement in aquaculture: a systematic review and implications on growth and adoption viability. *Sustain. (Switz.)* 15 (16), 12500. <https://doi.org/10.3390/SU151612500/S1>.
- Mair, G.C., Halwart, M., Derun, Y., Costa-Pierce, B.A., 2023. A decadal outlook for global aquaculture. *J. World Aquac. Soc.* 54 (2), 196–205. <https://doi.org/10.1111/JWAS.12977>.
- Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. *Anim. Feed Sci. Technol.* 197, 1–33. <https://doi.org/10.1016/j.anifoodsci.2014.07.008>.
- Malematja, E., Manyelo, T.G., Sebola, N.A., Kolobe, S.D., Mabelebele, M., 2023. The accumulation of heavy metals in feeder insects and their impact on animal production. *Sci. Total Environ.* 885, 163716 <https://doi.org/10.1016/J.SCITOTENV.2023.163716>.
- Maroušek, J., Strunecký, O., Maroušková, A., 2023. Insect rearing on biowaste represents a competitive advantage for fish farming. *Rev. Aquac.* 15 (3), 965–975. <https://doi.org/10.1111/RAQ.12772>.

- Mastoraki, M., Mollá Ferrándiz, P., Vardali, S.C., Kontodimas, D.C., Kotzamanis, Y.P., Gasco, L., Chatzifotis, S., Antonopoulou, E., 2020. A comparative study on the effect of fish meal substitution with three different insect meals on growth, body composition and metabolism of European seabass (*Dicentrarchus labrax* L.). *Aquaculture* 528, 735511. <https://doi.org/10.1016/j.aquaculture.2020.735511>.
- Mohan, K., Rajan, D.K., Muralisankar, T., Ganesan, A.R., Sathishkumar, P., Revathi, N., 2022. Use of black soldier fly (*Hermetia illucens* L.) larvae meal in aquafeeds for a sustainable. *Aquac. Ind.: A Rev. Future needs. Aquac.* 553, 738095 <https://doi.org/10.1016/j.aquaculture.2022.738095>.
- Moutinho, S., Pedrosa, R., Magalhães, R., Oliva-Teles, A., Parisi, G., Peres, H., 2021. Black soldier fly (*Hermetia illucens*) pre-pupae larvae meal in diets for European seabass (*Dicentrarchus labrax*) juveniles: effects on liver oxidative status and fillet quality traits during shelf-life. *Aquaculture* 533, 736080. <https://doi.org/10.1016/j.aquaculture.2020.736080>.
- Ng, W.-K., Liew, F.-L., Ang, L.-P., Wong, K.-W., 2001. Potential of mealworm (*Tenebrio molitor*) as an alternative protein source in practical diets for African catfish. (*Clarias gariepinus*). *Aquac. Res.* 32 (SUPPL. 1), 273–280. <https://doi.org/10.1046/j.1355-557x.2001.00024.x>.
- Niyonsaba, H.H., Hohler, J., Kooistra, J., van der Fels-Klerx, H.J., Meuwissen, M.P.M., 2021. Profitability of insect farms. *J. Insects Food Feed* 7 (5), 923–934. <https://doi.org/10.3920/JIFF2020.0087>.
- Nogales-Mérida, S., Gobbi, P., Józefiak, D., Mazurkiewicz, J., Dudek, K., Rawski, M., Kierończyk, B., Józefiak, A., 2019. Insect meals in fish nutrition. In: *Reviews in Aquaculture*, Vol. 11. Wiley-Blackwell, pp. 1080–1103. <https://doi.org/10.1111/raq.12281>.
- Ogunji, J., Toor, R.U.-A.S., Schulz, C., Kloas, W., 2008. Growth Performance, nutrient utilization of Nile tilapia (*Oreochromis niloticus*) fed housefly maggot meal (Maggmeal) diets. *Turk. J. Fish. Aquat. Sci.* 8 (1), 141–147. (<https://www.trjfas.org/abstract.php?lang=en&id=602>).
- Piccolo, J.J., 2017. The Land Ethic and conservation of native salmonids. *Ecol. Freshw. Fish.* 26 (1), 160–164. <https://doi.org/10.1111/EFW.12263>.
- Pippinato, L., Gasco, L., Di Vita, G., Mancuso, T., 2020. Current scenario in the European edible-insect industry: a preliminary study. *J. Insects Food Feed* 6 (4), 371–381. <https://doi.org/10.3920/JIFF2020.0008>.
- Precup, G., Verweris, E., Azzollini, D., Rivero-Pino, F., Zakidou, P., Germini, A., Precup, G., Verweris, E., Azzollini, D., Zakidou, P., Germini, A., Rivero-Pino, F., 2022. The safety assessment of insects and products thereof as novel foods in the European Union. *Nov. Foods Edible Insects Eur. Union* 123–146. https://doi.org/10.1007/978-3-031-13494-4_7.
- Pulido, L., Secci, G., Maricchiolo, G., Gasco, L., Gai, F., Serra, A., Conte, G., Parisi, G., 2022. Effect of dietary black soldier fly larvae meal on fatty acid composition of lipids and sn-2 position of triglycerides of marketable size gilthead sea bream fillets. *Aquaculture* 546, 737351. <https://doi.org/10.1016/j.aquaculture.2021.737351>.
- Qin, C., Zhang, Y., Liu, W., Xu, L., Yang, Y., Zhou, Z., 2014. Effects of chito-oligosaccharides supplementation on growth performance, intestinal cytokine expression, autochthonous gut bacteria and disease resistance in hybrid tilapia *Oreochromis niloticus* ♀ × *Oreochromis aureus* ♂. *Fish. Shellfish Immunol.* 40 (1), 267–274. <https://doi.org/10.1016/j.fsi.2014.07.010>.
- Rema, P., Saravanan, S., Armenjon, B., Motte, C., Dias, J., 2019. Graded Incorporation of Defatted Yellow Mealworm (*Tenebrio molitor*) in Rainbow Trout (*Oncorhynchus mykiss*) diet improves growth performance and nutrient retention. *Anim* 9 (4), 187. <https://doi.org/10.3390/ANI9040187>.
- Renna, M., Schiavone, A., Gai, F., Dabbou, S., Lussiana, C., Malfatto, V., Prearo, M., Capucchio, M.T., Biasato, I., Biasibetti, E., De Marco, M., Brugiapaglia, A., Zoccarato, L., Gasco, L., 2017. Evaluation of the suitability of a partially defatted black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (*Oncorhynchus mykiss* Walbaum) diets. *J. Anim. Sci. Biotechnol.* 8 (1), 1–13. <https://doi.org/10.1186/s40104-017-0191-3/TABLES/7>.
- Rimoldi, S., Antonini, M., Gasco, L., Moroni, F., Terova, G., 2021. Intestinal microbial communities of rainbow trout (*Oncorhynchus mykiss*) may be improved by feeding a *Hermetia illucens* meal/low-fishmeal diet. *Fish. Physiol. Biochem.* 47 (2), 365–380. <https://doi.org/10.1007/s10695-020-00918-1>.
- Rimoldi, S., Ceccotti, C., Brambilla, F., Faccenda, F., Antonini, M., Terova, G., 2023. Potential of shrimp waste meal and insect exuvia as sustainable sources of chitin for fish feeds. *Aquaculture* 567, 739256. <https://doi.org/10.1016/j.aquaculture.2023.739256>.
- Ringø, E., Sperstad, S., Myklebust, R., Refstie, S., Kroghdal, Å., 2006. Characterisation of the microbiota associated with intestine of Atlantic cod (*Gadus morhua* L.). *Aquaculture* 261 (3), 829–841. <https://doi.org/10.1016/j.aquaculture.2006.06.030>.
- Romano, N., Fischer, H., Kumar, V., Francis, S.A., Sinha, A.K., 2022. Productivity, conversion ability, and biochemical composition of black soldier fly (*Hermetia illucens*) larvae fed with sweet potato, spent coffee or dough. *Int. J. Trop. Insect Sci.* 42 (1), 183–190. <https://doi.org/10.1007/s42690-021-00532-5/METRICS>.
- Roncarati, A., Gasco, L., Parisi, G., Terova, G., 2015. Growth performance of common catfish (*Ameiurus melas* Raf.) fingerlings fed mealworm (*Tenebrio molitor*) diet. *J. Insects Food* 1 (3), 233–240. <https://doi.org/10.3920/JIFF2014.0006>.
- Rossi, G., Ojha, S., Müller-Belecke, A., Schlüter, O.K., 2023. Fresh aquaculture sludge management with black soldier fly (*Hermetia illucens* L.) larvae: investigation on bioconversion performances. *Sci. Rep.* 13 (1), 1–12. <https://doi.org/10.1038/s41598-023-48061-0>.
- S. Elserafy, S., H. Abdel-Hameid, N.-A., A. Abdel-Salam, H., M. Dakrouni, A., 2021. Effect of shrimp waste extracted chitin on growth and some biochemical parameters of the Nile tilapia. *Egypt. J. Aquat. Biol. Fish.* 25 (1), 313–329. <https://doi.org/10.21608/ejafb.2021.143244>.
- Sánchez-Muros, M.-J., Barroso, F.G., Manzano-Agugliaro, F., 2014. Insect meal as renewable source of food for animal feeding: a review. *J. Clean. Prod.* 65, 16–27. <https://doi.org/10.1016/j.jclepro.2013.11.068>.
- Sankian, Z., Khosravi, S., Kim, Y.O., Lee, S.M., 2018. Effects of dietary inclusion of yellow mealworm (*Tenebrio molitor*) meal on growth performance, feed utilization, body composition, plasma biochemical indices, selected immune parameters and antioxidant enzyme activities of mandarin fish (*Siniperca scherzeri*) juveniles. *Aquaculture* 496. <https://doi.org/10.1016/j.aquaculture.2018.07.012>.
- Schrögel, P., Wätjen, W., 2019. Insects for food and feed-safety aspects related to mycotoxins and metals. *Foods* 8 (8), 288. <https://doi.org/10.3390/FOODS8080288>.
- Sheppard, D.C., Tomberlin, J.K., Joyce, J.A., Kiser, B.C., Sumner, S.M., 2002. Rearing methods for the black soldier fly (diptera: Stratiomyidae). *J. Med. Entomol.* 39 (4), 695–698. <https://doi.org/10.1603/0022-2585-39.4.695>.
- Shi, F., Qiu, X., Nie, L., Hu, L., Babu, V. S., Lin, Q., Zhang, Y., Chen, L., Li, J., Lin, L., Qin, Z., 2020. Effects of oligochitosan on the growth, immune responses and gut microbes of tilapia (*Oreochromis niloticus*). *Fish. Shellfish Immunol.* 106, 563–573. <https://doi.org/10.1016/j.fsi.2020.07.049>.
- Sogari, G., Bellezza Oddon, S., Gasco, L., van Huis, A., Sprangers, T., Mancini, S., 2023. Review: Recent advances in insect-based feeds: From animal farming to the acceptance of consumers and stakeholders. In: *Animal*, Vol. 17. Elsevier B.V. <https://doi.org/10.1016/j.animal.2023.100904>.
- Stadlander, T., Stamer, A., Buser, A., Wohlfahrt, J., Leiber, F., Sandrock, C., 2017. *Hermetia illucens* meal as fish meal replacement for rainbow trout on farm. *J. Insects Food Feed* 3 (3), 165–175. <https://doi.org/10.3920/JIFF2016.0056>.
- Stankus, A. (2021, May). State of World Aquaculture 2020 and Regional Reviews: FAO Webinar Series. FAO Aquaculture Newsletter, 17–18. (<https://www.proquest.com/docview/2544287180?pq-origsite=gscholar&fromopenview=true>).
- St-Hilaire, S., Sheppard, C., Tomberlin, J.K., Irving, S., Newton, L., McGuire, M.A., Mosley, E.E., Hardy, R.W., Sealey, W., 2007. Fly prepupae as a feedstuff for rainbow trout, *Oncorhynchus mykiss*. *J. World Aquac. Soc.* 38 (1), 59–67. <https://doi.org/10.1111/j.1749-7345.2006.00073.x>.
- Su, J., Gong, Y., Cao, S., Lu, F., Han, D., Liu, H., Jin, J., Yang, Y., Zhu, X., Xie, S., 2017. Effects of dietary *Tenebrio molitor* meal on the growth performance, immune response and disease resistance of yellow catfish (*Pelteobagrus fulvidraco*). *Fish. Shellfish Immunol.* 69, 59–66. <https://doi.org/10.1016/j.fsi.2017.08.008>.
- Terova, G., Gini, E., Gasco, L., Moroni, F., Antonini, M., Rimoldi, S., 2021. Effects of full replacement of dietary fishmeal with insect meal from *Tenebrio molitor* on rainbow trout gut and skin microbiota. *J. Anim. Sci. Biotechnol.* 12 (1) <https://doi.org/10.1186/s40104-021-00551-9>.
- Terova, G., Rimoldi, S., Ascione, C., Gini, E., Ceccotti, C., Gasco, L., 2019. Rainbow trout (*Oncorhynchus mykiss*) gut microbiota is modulated by insect meal from *Hermetia illucens* prepupae in the diet. *Rev. Fish. Biol.* 29 (2), 465–486. <https://doi.org/10.1007/s11160-019-09558-Y/METRICS>.
- Tippayadara, N., Dawood, M.A.O., Krutmuang, P., Hoseinifair, S.H., Doan, H., Van, Paolucci, M., 2021. Replacement of fish meal by black soldier fly (*Hermetia illucens*) larvae meal: effects on growth, haematology, and skin mucus immunity of Nile tilapia, (*Oreochromis niloticus*). *Animals* 11 (1), 193. <https://doi.org/10.3390/ANI11010193>.
- Tomberlin, J.K., Sheppard, D.C., 2002. Factors influencing mating and oviposition of black soldier flies (Diptera: Stratiomyidae) in a colony. *J. Entomol. Sci.* 37 (4), 345–352. <https://doi.org/10.18474/0749-8004-37.4.345>.
- Tran, G., Heuzé, V., Makkar, H.P.S., 2015. Insects in fish diets. *Anim. Front.* 5 (2), 37–44. <https://doi.org/10.2527/AF.2015-0018>.
- van der Spiegel, M., 2016. Safety of foods based on insects. *Regul. Saf. Tradit. Ethn. Foods* 205–216. <https://doi.org/10.1016/B978-0-12-800605-4.00011-6>.
- van Huis, A., 2019. Insects as food and feed, a new emerging agricultural sector: a review. *J. Insects Food Feed* 2020, 6(1), 27–44. <https://doi.org/10.3920/JIFF2019.0017>.
- van Huis, A., 2020. Insect pests as food and feed. *J. Insects Food Feed* 6 (4), 327–331. <https://doi.org/10.3920/JIFF2020.X004>.
- Van Huis, A., Rumpold, B., Maya, C., Roos, N., 2021. Nutritional qualities and enhancement of edible insects. *Annu. Rev. Nutr.* 41 (1), 551–576. <https://doi.org/10.1146/ANNUREV-NUTR-041520-010856/CITE/REFWORKS>.
- Verbeke, W., Sans, P., Van Loo, E.J., 2015. Challenges and prospects for consumer acceptance of cultured meat. *J. Integr. Agric.* 14 (2), 285–294. [https://doi.org/10.1016/S2095-3119\(14\)60884-4](https://doi.org/10.1016/S2095-3119(14)60884-4).
- Wang, G., Peng, K., Hu, J., Mo, W., Wei, Z., Huang, Y., 2021. Evaluation of defatted *Hermetia illucens* larvae meal for Litopenaeus vannamei: effects on growth performance, nutrition retention, antioxidant and immune response, digestive enzyme activity and hepatic morphology. *Aquac. Nutr.* 27 (4), 986–997. <https://doi.org/10.1111/ANU.13240>.
- Wang, Y.S., Shelomi, M., 2017. Review of black soldier fly (*Hermetia illucens*) as animal feed and human food, 2017, Vol. 6, 91 *Foods* 6 (10), 91. <https://doi.org/10.3390/FOODS6100091>.
- Wang, Y. ru, Wang, L., Zhang, C. xiao, Song, K., 2017. Effects of substituting fishmeal with soybean meal on growth performance and intestinal morphology in orange-spotted grouper (*Epinephelus coioides*). *Aquac. Rep.* 5, 52–57. <https://doi.org/10.1016/j.aqrep.2016.12.005>.
- Westheim, A.J.F., Stoffels, L.M., Dubois, L.J., van Bergenhenegouwen, J., van Helvoort, A., Langen, R.C.J., Shiri-Sverdlov, R., Theys, J., 2023. The modulatory effects of fatty acids on cancer progression. *Biomedicines* 11 (2), 280. <https://doi.org/10.3390/BIOMEDICINES11020280>.
- Wethashinge, P., Hansen, J., Nøklund, D., Lagos, L., Rawski, M., Øverland, M., 2021. Full-fat black soldier fly larvae (*Hermetia illucens*) meal and paste in extruded diets for Atlantic salmon (*Salmo salar*): effect on physical pellet quality, nutrient

- digestibility, nutrient utilization and growth performances. *Aquaculture* 530, 735785. <https://doi.org/10.1016/J.AQUACULTURE.2020.735785>.
- Xiang, J., Qin, L., Zhao, D., Xiong, F., Wang, G., Zou, H., Li, W., Li, M., Song, K., Wu, S., 2020. Growth performance, immunity and intestinal microbiota of swamp eel (*Monopterus albus*) fed a diet supplemented with house fly larvae (*Musca domestica*). *Aquac. Nutr.* 26 (3) <https://doi.org/10.1111/anu.13029>.
- Xiao, X., Jin, P., Zheng, L., Cai, M., Yu, Z., Yu, J., Zhang, J., 2018. Effects of black soldier fly (*Hermetia illucens*) larvae meal protein as a fishmeal replacement on the growth and immune index of yellow catfish (*Pelteobagrus fulvidraco*). *Aquac. Res.* 49 (4), 1569–1577. <https://doi.org/10.1111/ARE.13611>.
- Yu, S.H., Zhu, K.Y., Zhang, F., Wang, J., Yuan, H., Chen, Y., Liu, T.X., 2023. The histone demethylase Jmjd3 regulates zebrafish myeloid development by promoting *spi1* expression. *Biochimica et Biophysica Acta (BBA). Gene Regulatory Mechanisms*.
- Zarantonello, M., Randazzo, B., Gioacchini, G., Truzzi, C., Giorgini, E., Riolo, P., Gioia, G., Bertolucci, C., Osimani, A., Cardinaletti, G., Lucon-Xiccato, T., Milanović, V., Annibaldi, A., Tulli, F., Notarstefano, V., Ruschioni, S., Clementi, F., Olivotto, I., 2020. Zebrafish (*Danio rerio*) physiological and behavioural responses to insect-based diets: a multidisciplinary approach. *Sci. Rep.* 10 (1) <https://doi.org/10.1038/s41598-020-67740-w>.