



Review Article

Recent advances in the utilization of insects as an ingredient in aquafeeds: A review



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ABSTRACT

The aquafeed industry continues to expand in response to the rapidly growing aquaculture sector. However, the identification of alternative protein sources in aquatic animal diets to replace conventional sources due to cost and sustainability issues remains a major challenge. Recently, insects have shown tremendous results as potential replacers of fishmeal in aquafeed. The present study aimed to review the utilization of insects in aquafeeds and their effects on aquatic animals' growth and feed utilization, immune response and disease resistance, and fish flesh quality and safety. While many insect species have been investigated in aquaculture, the black soldier fly (*Hermetia illucens*), and the mealworm (*Tenebrio molitor*) are the most studied and most promising insects to replace fishmeal in aquafeed. Generally, insect rearing conditions and biomass processing methods may affect the product's nutritional composition, digestibility, shelf life and required insect inclusion level by aquatic animals. Also, insect-recommended inclusion levels for aquatic animals vary depending on the insect species used, biomass processing method, and test organism. Overall, while an appropriate inclusion level of insects in aquafeed provides several nutritional and health benefits to aquatic animals, more studies are needed to

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establish optimum requirements levels for different aquaculture species at different stages of development and under different culture systems.

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1. Introduction

The global population is expected to reach nearly 10 billion people by 2050 (United Nations, 2019). Therefore, the food production sector, particularly animal protein production will play a critical role in food and nutrition security. In most global communities, fish is the cheapest and most readily available source of animal protein (Maulu et al., 2020). Aquaculture is not only the fastest-growing food production sector but also a major contributor to global food fish (Food and Agriculture Organization [FAO], 2020). Besides, aquaculture is the most sustainable and efficient way of producing aquatic products (FAO, 2020; Maulu et al., 2021a). However, the increasing costs of production in aquaculture due to the rising cost of feeding threaten the sustainability of the sector (Dawood, 2021). This is primarily caused by the overdependence of intensive aquaculture production on fishmeal and fish oils as major feed ingredients whose prices continue to rise due to declining production (Dawood, 2022; Hazreen-Nita et al., 2022). In addition, the food-feed-fuel competition for the limited resources under the current changing climatic conditions has drastically affected the availability of conventional feedstuffs such as fishmeal, soybean and cereals, leading to a decline in availability and high volatility in feed ingredient prices (Mugwanya et al., 2022). Besides, plant-based ingredients have been reported to cause negative side effects in the gut of carnivorous fish due to the presence of anti-nutritional factors (Zhou et al., 2018) and complex indigestible carbohydrates (Gaudioso et al., 2021), consequently impacting growth and welfare of the fish. Therefore, recent studies have focused on evaluating potentially sustainable alternatives including insects (Li et al., 2019; Alves et al., 2021; Terova et al., 2021), bacteria (Maulu et al., 2021b; Li et al., 2021) and organic by-products (Mo et al., 2014; Cheng et al., 2017). Among these, insects have attracted the most attention due to their wide application in aquaculture and ease of production.

Insects are reported to contain high crude protein content of 34% to 74% dry matter, DM (Freccia et al., 2020; Gasco et al., 2020). However, most whole-insects contain 42% to 63.3% crude protein on a dry matter basis (Alfiko et al., 2022) with up to 74% reported when insect meal is defatted (Alfiko et al., 2022). Additional nutritional value includes a well-balanced essential amino acid (EAA) profile resembling that of fishmeal, high lipid (10% to 30%), DM level (albeit high variability in fatty acid profiles), a good source of vitamins like vitamin B₁₂, and some bio-available minerals like iron and zinc (Alegbeleye et al., 2012; Gasco et al., 2020). Furthermore, insect meal contains bioactive compounds (e.g., chitin, fatty acids and antimicrobial peptides) with prebiotic, antioxidant and antimicrobial properties that promote animal health and counteract antimicrobial resistance (Gasco et al., 2018; Veldkamp et al., 2022). However, the nutritional composition varies with insect species (DeFoliart, 1995; Barroso et al., 2014), the rearing process (Zarantoniello et al., 2020) and the production process of the protein (Ramos-Elorduy et al., 2002), suggesting that the proximate composition could be modified to suit specific requirements. For instance, defatting increases the protein content in insect meal (Alfiko et al., 2022), while rearing the insects on substrate rich in n-3 polyunsaturated fatty acids (PUFAs) could increase the PUFA

profile content in insects (Zarantoniello et al., 2020). Unlike fishmeal and plant-based protein, insects can be produced intensively within a short time with little need for arable land, reduced water consumption/utilization, lower greenhouse gas (GHG) emissions, and bio-waste conversion (Gasco et al., 2020; Pulido-Rodriguez et al., 2021). Thus, insect farming is considered sustainable due to its low ecological footprint. Also, when used in diets with multiple ingredients including plant-based proteins, insects have shown potential to counteract the negative effects on growth and gut health in carnivorous species, which are usually common when fishmeal is replaced with plant protein (Randazzo et al., 2021; Pulido-Rodriguez et al., 2021; Gaudioso et al., 2021).

The unique properties of insects and their suitability for application in aquafeeds as fishmeal and fish oil replacement have become a hotspot for research in aquaculture. Numerous authors have reviewed the existing literature to identify findings that provide a map for future development. Most of these studies have focused on the nutritional composition of different insects used in aquafeeds, their production technology, and prospects (Henry et al., 2015; Nogales-Mérida et al., 2018; Ameixa et al., 2020; Gasco et al., 2020; Oonincx and Finke, 2021; Alfiko et al., 2022). Others have further highlighted the effect of insects in aquafeed on aquatic animals (Wang and Shelomi, 2017; Freccia et al., 2020; Hawkey et al., 2021). English et al. (2021) reviewed the advancements in the production methods for BSF and their application in salmonids, while Priyadarshana et al. (2021) reviewed the application of BSF meal focussing on growth performance and body composition in finfish. Mousavi et al. (2020) reviewed the functional properties of insects focussing on their immunomodulatory and physiological effects on aquatic animals. Other reviews, such as those of Zarantoniello et al. (2020) and Shafique et al. (2021) only focused on a single insect species and its effect on fish. Hodar et al. (2020) broadly looked at a range of alternative protein alternatives (including insects) as potential fishmeal and fish oil replacement in aquafeeds while Liland et al. (2021) performed a meta-analysis on the nutritional value of insects in aquafeeds. More recently, Alfiko et al. (2022) reviewed the status and trends in the application of insects in fish feeds. In this study, we provide a more comprehensive overview of the most recent advances in the utilization of insects as a promising aquafeed ingredient. This paper attempts to bridge the gap in the existing literature by presenting information on the response of different aquaculture species to insect-based feeds and opportunities for further improvement.

2. Insect species utilized in aquafeed

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

et al., 2020; Shafique et al., 2021). Consequently, some have been incorporated into aquafeed formulations for different aquatic species, yielding interesting results. The most promising insect species whose meal has been used to replace fish meal and/or fish oils include the black soldier fly (BSF, *Hermetia illucens*), the yellow mealworm (TM, *Tenebrio molitor*) and the common housefly (MD, *Musca domestica*) (Belforti et al., 2015; Gasco et al., 2020; Iaconisi et al., 2019; Sogari et al., 2019). So far, BSF, TM and MD have well-documented production processes. Although some of the insects like the house fly are known to be parasitic and disease vectors, other species like the BSF are considered symbiotic (Menino and Murta, 2021) as they can be propagated without causing any known harm to humans. Unlike animals, the feed conversion rate and GHG emissions of insects are much lower in a certain temperature range since insects do not use energy to maintain their body temperature in a strict range (Belforti et al., 2015). Irrespective of the different methods of propagation and production of different species, insects have shown promising results for potential use as a protein and oil source in aquafeed.

Many studies have revealed that insect meals and oil can partially or completely replace the fish and soybean meals and oils that are commonly used in aquaculture production (Henry et al., 2015; Nogales-Mérida et al., 2018; Fawole et al., 2020; Tilami et al., 2020; Xu et al., 2020a; Hender et al., 2021). Insects such as the BSF have been extensively studied, not only in fish culture but also in poultry and swine (Sogari et al., 2019). In aquaculture, many studies have revealed positive results when BSF meal was used as a substitute for fish meal for many species such as whiteleg shrimp (*Litopenaeus vannamei*) (Richardson et al., 2021), barramundi (*Lates calcarifer*) (Hender et al., 2021), climbing perch (*Anabas testudineus*) (Mapanao et al., 2021), Nile tilapia (*Oreochromis niloticus*) (Were et al., 2021), African catfish (*Clarias gariepinus*) (Fawole et al., 2020), Japanese sea bass (*Lateolabrax japonicus*) (Wang et al., 2019), Atlantic salmon (*Salmo salar*) (Lock et al., 2016; Stenberg et al., 2019), Siberian sturgeon (*Acipenser baerii*) (Zarantoniello et al., 2021), gilthead sea bream (*Sparus aurata*) (Randazzo et al., 2021), clownfish (*Amphiprion ocellaris*) (Vargas-Abúndez et al., 2019) and in rainbow trout (*Oncorhynchus mykiss*) (Cardinaletti et al., 2019) to produce food fish. In the aforementioned species, BSF improved various growth parameters as well as the immune response to some diseases affecting aquatic species. Also, TM has shown positive results when utilized in the diets of many aquatic species, such as yellow catfish (Su et al., 2017), gilthead seabream (Fabrikov et al., 2021), largemouth bass (*Micropterus salmoides*) (Su et al., 2022), seabass (*Dicentrarchus labrax*) (Reyes et al., 2020), narrow-clawed crayfish (*Pontastacus leptodactylus*) (Mazlum et al., 2021), olive flounder (*Paralichthys olivaceus*) (Jeong et al., 2021), black porgy (*Acanthopagrus schlegelii*) (Jeong et al., 2022) and rainbow trout (Su et al., 2017; Melenchón et al., 2021). Furthermore, TM has a relatively high nutritional value as well as being a rich source of essential amino acids (methionine), lipids and fatty acids, that vary based on the developmental stage of the larvae (Shafique et al., 2021).

Other species of insects that have yielded promising results in aquatic animals include the superworm (*Zophobas morio*) in Nile tilapia (Alves et al., 2021) and the silkworm (*Bombyx mori*) in Pacific white shrimp (*L. vannamei*) (Rahimnejad et al., 2019) as well as its application in many other cultured fish and shrimp species (Sankian et al., 2018; Feng et al., 2019; Ido et al., 2019; Su et al., 2017). Despite limited information existing, the nutritional properties of insects for use in aquafeed are likely to vary across and within aquaculture species depending on developmental stage, culture media and rearing conditions (Liu et al., 2017; Yu et al., 2021). Overall, the proximate composition of most insects decreases with advancement in the developmental stage.

3. Insect biomass production and processing for aquafeed

The conversion of insects into aquafeed ingredients is an important step that determines their required level and effectiveness in aquatic animals. With the discovery of insects and their potential for replacing fishmeal in animal feeds, there is a danger that natural harvests could have serious biodiversity conservation-related issues. Hence, the mass production of insects for commercial-scale industry from agricultural organic residues and biowaste for feed purposes or food is a promising and sustainable approach (Varelas, 2019). However, due to variations that occur during culturing under controlled environments for insect mass production, the nutritional value is also expected to vary (Varelas, 2019). For example, Cortes Ortiz et al. (2016) noted that the artificial diets required by insects differ not only in presentation, from liquid to solid, but also in nutritive value, the feeding adaptation of the insect, insect species and the pre-manufacture method. Additionally, insects have been reported to have variable fatty acid profiles, particularly having a low level of PUFAs. PUFAs have important health benefits in humans and are required for optimal growth and development in children (Maulu et al., 2021c). Therefore, it is important to incorporate PUFA enrichment methods such as rearing insects in n-3 PUFA-rich substrates as demonstrated by Zarantoniello et al. (2020). Erbland et al. (2020) reported that insects can accumulate eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) by modifying their rearing substrates. The authors supplemented a chicken feed diet with increasing concentrations of salmon oil (0% to 42%) to the substrate over an increasing number of days (0 to 8 d) to improve the concentration of omega-3 fatty acids in BSF larvae. The accumulation of EPA and DHA was achieved in BSF and TM larvae by feeding the insects with round sardinella (*Sardinella aurita* Valenciennes, 1847) and black-spot seabream (*Pagellus bogaraveo*, Brünnich, 1768) discards. Similar findings were reported by Romero-Lorente et al. (2022) in TM larvae, however, the authors suggested that longer pre-treatment, for 5 days, would be required. Tirtawijaya and Choi (2021) fortified BSF larvae substrate with squid liver at different concentrations of 2.5% to 20% and a concentration of 5% was reportedly required to achieve a better accumulation of EPA and DHA in the insect. Very long-chain polyunsaturated fatty acids (VLCPUFAs) could be altered in BSF larvae by modifying the diet of the insect (Barroso et al., 2017). Overall, these studies indicated the possibility of improving the nutritional value of insects for use in aquafeed by modifying their rearing conditions. However, the fatty acid composition of the substrate and the weight of the insect larvae are determinants of the fatty acid profile (Ewald et al., 2020).

In a review by Varelas (2019), the different methods of insect biomass production from food waste are presented in more detail. For insects to remain a sustainable protein source in aquafeed, low-cost production technology for commercial industries is very crucial. Thus, various biomass processing methods have recently been reviewed. The most recent one is that of Parniakov et al. (2021) where a comprehensive overview of insect biomass processing methods is discussed.

So far, several parts of insects, including meal (Ido et al., 2019), the pulp (Xu et al., 2020b), paste (Weththasinghe et al., 2021), frass (Yildirim-Aksoy et al., 2020) and oil (Kumar et al., 2021) have been used as ingredients in aquafeed. However, the meal, either full-fat or defatted is the most commonly used form of insects in aquafeed. For example, the BSF is processed mainly into a dry meal using partially defatted or full-fat larvae (English et al., 2021). In yellowtail (*Seriola quinqueradiata*), feeding the fish with completely defatted BSF larvae meal enhanced the growth of the fish compared with using partially defatted larvae (Ido et al., 2021). Therefore, defatting insects before milling for inclusion in aquafeed could

yield better results in many fish species. For commercial use, BSF is processed using technologies like drying ovens (Dortmans et al., 2017) while defatting is achieved using an oil press or centrifuge (English et al., 2021). Drying at the right temperature is important particularly for storage purposes as it prevents microbial activity from affecting the nutritional value of the product (Dortmans et al., 2017). Defatting is recommended because it renders a product with high protein content and low moisture which is ideal for feeding and storage (Dortmans et al., 2017). As BSF larvae are usually dried at high temperatures (>90 °C), there are concerns that there will be a decrease in the nutrient (protein) digestibility coefficient which could negatively affect fish growth (Weththasinghe et al., 2021; Xu et al., 2020a). However, few studies have comprehensively investigated the effect of processing such as drying temperature and pressure of partially defatted, fully defatted, or full-fat BSF larvae meals in diets for fish (English et al., 2021). Therefore, further research is needed in that regard. Most studies simply investigate the effect of one processing method e.g., partial defatting in comparison to the fishmeal control diet, although they try to regulate temperature below 90 °C when drying the larvae. The TM larvae can be fed fresh (Henry et al., 2015) or prepared as a meal by oven drying, sun drying or freeze-drying the larvae before grinding. As with BSF, processing of TM by defatting or utilizing it with full fat could affect acceptability and consequently maximum inclusion levels in diets (Shafique et al., 2021). However, defatted TM has been reported to provide the benefit of increased protein content and a more stable pelleting process of the feed (Shafique et al., 2021). Other insects such as the MD and earthworm (*Perionyx excavates*) could be processed by boiling in hot water followed by drying in an oven before being milled (Gbai et al., 2018). Interestingly, the mopane worm (*Imbrasia belina*) has been processed by first gutting it before boiling in brine and later sun-drying in preparation for grinding into a meal (Rapatsa and Moyo, 2017). Although degutting is mainly used for preservation purposes, the authors observed that the plant matter in the gut of the mopane worm could contain amylase activity. Further studies are necessary to investigate the effect of degutting the mopane worm before use in aquafeed. Different processing methods and recommended levels of different insect meals are summarized in Table 1.

4. Utilization in aquafeeds

4.1. Recommended levels in diets for aquatic animals

The incorporation of insects in aquafeed has been investigated and is considered a breakthrough in the efforts to replace fishmeal in many aquaculture species. Currently, a very limited number of studies have determined the optimal requirement levels of insect meals in aquafeed (Katya et al., 2017; Shekarabi et al., 2021; Tippayadara et al., 2021). What is available are mostly recommended levels based on the results yielded from insect meal inclusion in the diets mainly as replacements for fishmeal. The results reported so far regarding insect incorporation levels in aquafeeds have shown conflicting results depending on factors such as fish species, growth stage, feed formulation, insect biomass processing method and dietary administration period. A recent review of the meta-analysis studies on the nutritional value of insects in aquafeed indicates a high degree of variation regarding the maximum inclusion levels of insects in aquafeed based on these factors (Liland et al., 2021). Hence, the authors observed that 20% to 30% could be the maximum range for insect meal inclusion levels without adverse effects. Also, whether the diet is plant-based or animal-based appears to influence the insect requirement level of different species. Earlier reviews predominantly focused on inclusion levels of insect meals in freshwater species (Henry et al., 2015)

but recent reviews are broadening the scope to include marine species (English et al., 2021; Priyadarshana et al., 2021). This is because of the growing evidence that insect meal requirement levels between freshwater and marine aquaculture species could vary. However, there are no studies that have critically compared this in aquatic animals even though it is obvious that the nutritional requirements between the two are different. In some marine fish species, such as the European seabass (*D. labrax*), optimal growth had previously not been achieved by replacing fishmeal with full-fat insect meal at levels higher than 50% (Basto et al., 2021). This was attributed to n-3 long-chain polyunsaturated fatty acids (LC-PUFA) deficiencies (<0.7% DM) at higher fishmeal replacement levels (Skalli and Robin, 2004). A recent study by Basto et al. (2021), however, showed that up to 80% (360 g/kg) of fishmeal could be replaced by TM in the diet of *D. labrax* fingerlings without detrimental effects on growth and nutrient digestibility. As aquaculture is a diverse industry in terms of cultured species and their developmental stages, production systems used and culture conditions, more studies are required to investigate insect meal requirement levels in aquatic animals.

Most of the progress made in the utilization of insects in aquafeed has focused on replacing fishmeal due to rising costs and sustainability issues. As such, most of the existing studies have investigated the effect of replacing fishmeal at different levels in the diets of aquatic animals with a view to partially or fully replace fishmeal. This has been done either by combining some insect species (Hoffmann et al., 2021) or singly, with amino acids supplemented to meet the EAA requirements of fish (Chemello et al., 2020). However, when used in combination, Hoffmann et al. (2021) reported that the type of insect meal had a crucial impact on fish growth and feed utilization parameters. In their study, the authors noted that combinations of full-fat larval stage TM and BSF meal performed better than combinations of imago stage tropical house cricket (*Gryllodes sigillatus*) and Turkestan cockroach (*Blattella lateralis*) in diets of sea trout (*Salmo trutta*) larvae. In Eurasian perch (*Perca fluviatilis*), fingerlings fed an experimental diet containing a combination of 50 g/kg house cricket and 50 g/kg of superworm (25% fishmeal replacement) had significantly lower growth compared to the control (Tilami et al., 2020). This was attributed to several factors including reduced feed intake (palatability), presence of chitin and oxidized fat. Insects have also been used singly or in combination with other ingredients to replace plant-based proteins in animal diets. For instance, BSF inclusion at 324 g/kg (47% replacement of vegetable mix) and BSF and protein by-product meal (PBM) inclusion levels at 81 and 206 g/kg, respectively (49% replacement of vegetable mix), led to faster growth of gilthead seabream in comparison to the vegetable mix and fishmeal only controls (Randazzo et al., 2021). This study is of interest because while it is important to look at studies in which insect meals are used to replace fishmeal in aquafeeds; it is also beneficial to compare the effects with insect replacement in commonly utilized plant-based diets.

The presence of chitin in insect meals could have beneficial effects on fish by shaping the gut microbial community and boosting the innate immune response when incorporated at moderate quantities ranging from 25 to 50 mg/kg (Esteban et al., 2001; Bruni et al., 2018). On the other hand, the effect of higher inclusion levels of insect meal has been reported to yield negative results in most species, and this has been associated with the increased level of chitin at higher levels (Kroeckel et al., 2012; Renna et al., 2017). For instance, BSF larvae meal incorporated at 400 g/kg (corresponding to a chitin level of 2 g/100 g DM) was reported to reduce dry matter and crude protein digestibility but did not affect growth in rainbow trout (*O. mykiss*) (Renna et al., 2017). BSF pre-pupae meal incorporated in diets of juvenile turbot (*Psetta maxima*) at levels higher

Table 1
Maximum recommended levels of insect meal for inclusion in aquafeed based on different insect biomass processing methods.

Fish species	Initial weight, g	Insect meal	Processing method	Recommended (Fish meal replacement)	Administration period	References
Red seabream (<i>Pargus major</i>)	24.9 ± 0.71	Yellow mealworm larvae (<i>Tenebrio molitor</i> , TM)	Ground and defatted	650 g/kg (100%)	4 wk	Ido et al. (2019)
Seabass (<i>Dicentrarchus labrax</i>)	10.7	Black soldier fly (BSF, <i>Hermetia illucens</i>) larvae	Larvae fed on a broiler diet	109 g/kg (30%)	49 d	Reyes et al. (2020)
	24.2 ± 7.59	Defatted BSF	Defatted using mechanical method	185 g/kg (25%)	118 d	Caimi et al. (2020b)
	53.39 ± 3.74	Full-fat TM larvae	Air-dried and ground	200 g/kg (40%)	71 d	Józefiak et al. (2019a)
	201.8 ± 13.9	Full-fat BSF	Larvae dried and ground	300 g/kg (30%)	5 wk	Huyben et al. (2019)
Rockfish (<i>Sebastes schlegeli</i>)	137 ± 10.5	Full-fat BSF prepupae meal	Frozen and ground	210 g/kg (50%)	98 d	Cardinaletti et al. (2019)
	3.11 ± 0.01	TM	Dried and ground	160 g/kg (19%)	8 wk	Khosravi et al. (2018)
Pacific white shrimp (<i>Litopenaeus vannamei</i>)	1.55 ± 0.5	Defatted TM larvae	Freeze dried, ground, and dried	205 g/kg (100%)	8 wk	Motte et al. (2019)
White shrimp (<i>L. vannamei</i>)	2.39 ± 0.49	Partially defatted or full defatted TM larvae	Oven dried and milled	100 g/kg (50%)	8 wk	Choi et al. (2018)
Sea trout (<i>Salmo trutta</i>)	5.08 ± 0.9	TM larvae	Hydrolyzed	100 g/kg (42%)	8 wk	Mikołajczak et al. (2020)
Nile tilapia (<i>Oreochromis niloticus</i>)	14.77 ± 2.09	BSF larvae	Dried in hot air and ground	100 g/kg (100%)	12 wk	Tippayadara et al. (2021)
	0.66	Maggot meal (<i>Musca domestica</i> , MD)	Killed in hot water, oven-dried, and ground	200 g/kg (100%)	90 d	Gbai et al. (2018)
	68.85 ± 0.24	MD larvae meal	Oven dried and milled	330 g/kg (75%)	10 wk	Wang et al. (2017)
Mandarin fish (<i>Siniperca scherzeri</i>) juveniles	8.65	MD larvae meal	Killed in hot water, oven-dried, and ground	250 g/kg (66.7%)	12 wk	Alofa and Abou (2020)
	20.8 ± 0.05	TM larvae	Freeze-dried and ground	300 g/kg (30%)	12 wk	Sankian et al. (2018)
Butter catfish (<i>Ompok pabda</i>)	0.6	Earthworm meal (<i>Perionyx excavates</i>)	Boiled, oven-dried, and ground	260.4 g/kg (75%)	8 wk	Chakraborty et al. (2021)
Asian sea bass (<i>Lates calcarifer</i>)	12.52 ± 0.52	Defatted superworm larvae (<i>Zophobas morio</i>)	Ground, defatted, oven-dried, and reground	120 g/kg (44%)	12 wk	Prachom et al. (2021)
Mozambique tilapia (<i>Oreochromis mossambicus</i>)	40 ± 2.5	Mopane worm (<i>Imbrasia belina</i>)	Gutted, cooked in brine & sundried	24 g/kg (60%)	51 d	Rapatsa and Moyo (2017)
African catfish (<i>Clarias gariepinus</i>)	4.00 ± 0.8	Field cricket (<i>Gryllus bimaculatus</i>) meal	Oven-dried and ground	300 g/kg (100%)	56 d	Taufek et al. (2018)
Red seabream (<i>P. major</i>)	10.4	Defatted MD larvae meal	Boiled, air-dried and milled	700 g/kg (100%)	4 wk	Hashizume et al. (2019)
	12.8	Defatted MD larvae meal	Boiled, air-dried and milled	400 g/kg (100%)	4 wk	Hashizume et al. (2019)

than 332 g/kg (chitin level ranging from 47 to 73 g/kg DM) led to reduced feed intake and feed conversion and subsequently reduced growth (Kroeckel et al., 2017). According to Soetemans et al. (2020), the crystalline nature of chitin present in some insects is what limits its utilization in aquafeed. Wang et al. (2020) found that this crystalline nature increases with the advance in developmental state of insects, particularly BSF from larvae to adults. For example, in Siberian sturgeon juveniles, the inclusion of highly defatted BSF meal from 185 to 375 g/kg (25% to 50% fishmeal replacement; 0.72 to 1.92 g/100 g chitin in feed) reduced the feed intake and apparent digestibility coefficient (ADC) of protein, while inclusion at 750 g/kg (100% fishmeal replacement; 3.75 g/100 g chitin in feed) led to complete rejection of the feed (Caimi et al., 2020a). Feeding sea trout (*S. trutta*) fingerlings with hydrolyzed TM at an inclusion level of at least 100 g/kg (9.3 g/kg chitin in feed; 42% fishmeal replacement) resulted in a significantly reduced protein efficiency ratio (Mikolajczak et al., 2020). However, whether insect biomass processing methods affect the chitin content in the meal is not yet clear and as such, further studies are required. Although Gasco et al. (2018) reported that the content level of chitin can be reduced through the extraction process or dietary enzyme inclusion to improve its digestibility; appropriate technologies have not yet been fully applied. Jayanegara et al. (2017) were able to completely remove chitin from cricket (*Gryllus assimilis*) by chemical digestion while reducing chitin levels from 7.7% dry matter to 3.5% by exoskeleton removal.

Besides the presence of chitin, negative effects observed in aquatic animals when insect meals are incorporated in aquafeeds can be attributed to lower levels of fatty acids in the diets in comparison to the fishmeal control diet (Zarantoniello et al., 2021). Insects have been reported to have lower levels of n-3 PUFA (Zarantoniello et al., 2020) and therefore without sufficient enrichment processes in the insect rearing process, this might translate to lower n-3 PUFA levels in the aquafeeds. For instance, in a study by Zarantoniello et al. (2021), diets in which 50% fishmeal was replaced by BSF had significantly lower n-3 fatty acids. Consequently, Siberian sturgeon fed these diets had significantly lower growth and specific growth rate than those fed the control diet. According to the authors, the fish spent energy converting linoleic acid and α -linolenic acid to EPA and DHA instead of utilizing the energy all for growth. Additionally, the authors reported lower diet acceptance in the fish-fed diets containing 50% insect meal thus, requirement levels might be affected by the palatability of the diets (Zarantoniello et al., 2021). However, several studies have shown that the absence of n-3 long-chain polyunsaturated fatty acids (LCPUFA) in terrestrial insects can be alleviated by feeding insects with diets rich in n-3 LCPUFA (Barroso et al., 2017; Fabrikov et al., 2020, 2021; Tirtawijaya and Choi, 2021).

In other studies, the negative effects when aquatic animals are fed with higher dietary levels of insect meal were attributed to the presence of non-protein nitrogen in some insects, which could lead to the overestimation of protein (Janssen et al., 2017). Nevertheless, the recommended levels of different insect meals under different processing methods for different fish species are presented in Table 1 below.

4.2. Effects of insect meal on aquatic animals

4.2.1. Growth and feed utilization

The growth performance and feed utilization effects of several insects have been studied in aquaculture. These include BSF (Fawole et al., 2020; Peng et al., 2021b), yellow mealworm (*T. molitor*) (Sankian et al., 2018), housefly (*M. domestica*) (Hashizume et al., 2019), mopane worm (*I. belina*) (Rapatsa and Moyo 2017), chironomid (Roncarati et al., 2019) and cricket

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

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

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

4.2.2. Antioxidant capacity

The effect of insect utilization in aquafeed on the antioxidant capacity of fish has been reported in numerous studies with promising results. A summary of the results reported by different studies is presented in Table 2. However, the results vary depending on the insect species and parts used in aquafeed. For example, dietary insect (such as BSF) meal as a replacement for fishmeal showed deleterious effects on the transcription of antioxidant enzymes and stress-related genes in the leukocytes of the head kidney (Stenberg et al., 2019). In the African catfish, substituting fishmeal with BSF at 75% did not impair the antioxidant status of

Table 2

A summary of some studies that have shown effects when insects were used as a protein source in aquafeed.

Insect species	Used part	Aquaculture species	Fish weight, g	Period	Inclusion level, %	Effect	References
Black soldier fly (<i>Hermetia illucens</i>)	Frass	Hybrid tilapia, Nile × Mozambique (<i>Oreochromis niloticus</i> × <i>O. mozambique</i>)	2.6 ± 0.04	12 wk	5 to 30	Improved protein efficiency, serum complement activity and resistance against <i>Flavobacterium columnare</i> and <i>Streptococcus iniae</i>	Yildirim-Aksoy et al. (2020)
	Meal	Rice field eel (<i>Monopterus albus</i>)	24.0 ± 0.02	10 wk	15.78	Improved growth performance and gut microbiota balance	Hu et al. (2020)
	Meal	Atlantic salmon (<i>Salmo salar</i>)	17.5 ± 7.5	8 wk	66 to 100	Down-regulation of stress and antioxidant-related gene expression in the leucocytes.	Stenberg et al. (2019)
	Defatted meal	Japanese seabass (<i>Lateolabrax japonicus</i>)	14.1 ± 0.17	8 wk	64	Enhanced feed intake but lowered serum properties, blood lipid and inhibited lipid deposition	Wang et al. (2019)
	Meal	African catfish (<i>Clarias gariepinus</i>)	4.0 ± 0.01	60 d	50	Improved growth performance and feed utilization and antioxidant enzymes.	Fawole et al. (2020)
	Meal	European sea bass (<i>Dicentrarchus labrax</i>)	50.0 ± 0.50	62 d	22.5	Reduced lipid oxidation in the fillet	Moutinho et al. (2021)
	Meal	Rainbow trout (<i>Oncorhynchus mykiss</i>)	32.0	10 wk	8 to 16	Successful prevention of soybean meal (SBM)-induced enteritis in the intestine and enhanced immune response	Kumar et al. (2021)
	Oil	Rainbow trout	32.0	10 wk	16	Improved serum-peroxidase activity and upregulation of kidney interleukin-8 (IL-8), tumour necrosis factor (TNF), and interferon regulatory factor 1 (IRF-1)	Kumar et al. (2021)
	Meal	Pre-smolt Atlantic salmon	49.0 ± 1.50	8 wk	85	Reduced the deposition of excess lipids in the pyloric caeca and stimulated xenobiotic metabolism.	Li et al. (2019)
	Meal	Rainbow trout	137.0 ± 10.50	98 d	50	Activation of immune related genes such as interleukin 10 (IL-10), TNF- α and toll-like receptor 5 (TLR-5)	Cardinaletti et al. (2019)
	Meal	Pacific white shrimp (<i>Litopenaeus vannamei</i>)	0.67 ± 0.15	4 wk	7.5	Improved weight gain, feed conversion ratio (FCR) and specific growth rate (SGR)	Richardson et al. (2021)
	Meal	Barramundi (<i>Lates calcarifer</i>)	1.74 ± 0.15	42 d	30	Improved growth and feed utilization, bactericidal activity and upregulation of immune-related genes such as interleukin 1 (IL-1) and IL-10	Hender et al. (2021)
	Oil	Barramundi	1.74 ± 0.15	42 d	30	Enhanced growth performance and upregulation of immune-related genes (IL-1 and IL-10)	Hender et al. (2021)
	Partially defatted meal	Rainbow trout	178.9 ± 9.81	78 d	50	Sensitivity and modulation of intestinal bacterial community and structure.	Bruni et al. (2018)
	Meal	Atlantic salmon	49.0 ± 1.5	8 wk	60	Modulation of intestinal microbiota, enrichment of beneficial bacteria	Li et al. (2021)
	Meal	Atlantic salmon	1400 ± 43	16 wk	15	Improved microbial richness and diversity related to immune responses and barrier function in the distal intestine	
	Oil	Mirror carp (<i>Cyprinus carpio</i> var. <i>specularis</i>)	2.74	8 wk	50 to 100	Enhanced growth and feed utilization and health parameters	Xu et al. (2020a)
	Meal	Atlantic Salmon	34	7 wk	12.5	Reduction in enterocyte steatosis in pyloric caeca improved distal intestine histology and enhanced plasma lysozyme content	Weththasinghe et al. (2021)
	Meal	Rainbow trout	201.8 ± 13.9	5 wk	30	Increased diversity and modulation of gut bacteria composition	Huyben et al. (2019)
	Pulp	Mirror carp	13.68 ± 0.02	8 wk	50	Decreased whole-body lipid content and increased antioxidant enzyme activity	

	Meal	Rainbow trout	100	131 d	50	Modulation of the gut microbial community by enhancing the abundance of bacteria taxa related to fish health	Rimoldi et al. (2021)
	Meal	Baltic prawn (<i>Palaemon adspersu</i>)	0.49 ± 0.1	60 d	18	Improved growth performance and survival	Mastoraki et al. (2020)
	Meal	Siberian sturgeon (<i>Acipenser baerii</i>)	640 ± 3.9	60 d	15	Improved gut microbiota composition and intestinal morphology but reduced mucosa thickness in the gastrointestinal tract.	Józefiak et al. (2019b)
	Meal	Siberian sturgeon		60 d	50	Lowered diet acceptance results in lowered growth and survival, decreased hepatic lipids and glycogen content, adverse effects on gut histology, but with a higher hepatic heat shock protein 70.1 (hsp70.1) gene expression	Zarantonello et al. (2021)
	Meal	Rainbow trout	53.4 ± 3.74	71 d	20	Improved growth performance and an increased count of beneficial bacteria in the intestine	Józefiak et al. (2019a)
Silkworm (<i>Bombyx mori</i> L.) pupae	Defatted meal	Pacific white shrimp (<i>L. vannamei</i>)	0.2 ± 0.02	8 wk	75 to 100	Improved digestibility, antioxidant capacity and reduced molting time.	Rahimnejad et al. (2019)
Mealworm beetle, (TM)	Meal	Giant river prawn (<i>Macrobrachium rosenbergii</i>)	3.26 ± 0.13	10 wk	12	Improved growth performance, immune response, disease resistance against <i>Lactococcus garvieae</i> , and <i>Aeromonas hydrophila</i> .	Feng et al. (2019)
	Defatted meal	Pacific white shrimp	1.5 to 1.6	8 wk	50	Improved growth and feed conversion ratio, enhanced resistance against early mortality syndrome (<i>Vibrio parahaemolyticus</i>)	Motte et al. (2019)
	Partially defatted meal	Rainbow trout	78.3 ± 6.24	154 d	50 to 100	Reduced apparent digestibility of crude protein	Chemello et al. (2020)
	Meal	Gilthead seabream (<i>Sparus aurata</i>)	105.2 ± 0.17	163 d	50	Establishment of novel nutritional niches in the gut	Antonopoulou et al. (2019)
	Meal	Gilthead seabream	86.97 ± 2.3	163 d	25	Best final weight, specific growth rate, weight gain, protein efficiency ratio and a lower feed conversion ratio	Piccolo et al. (2017)
	Meal	European sea bass	5.2 ± 0.82	70 d	50	Establishment of novel nutritional niches in the gut	Antonopoulou et al. (2019)
	Meal	Rainbow trout	115.2 ± 14.21	90 d	60	Improved specialized gut bacterial community	Antonopoulou et al. (2019)
	Defatted meal	Red seabream (<i>Pargus major</i>)	30.4	8 wk	10	Increased resistance against pathogenic <i>Edwardsiella tarda</i> bacteria	Ido et al. (2019)
	Meal	Rainbow trout	115.6 ± 14	90 d	50	Increased activity of the antioxidant enzymes in the intestine and reduction of lipid peroxidation. Also increased antibacterial activity of the serum	Henry et al. (2018)
	Meal	European sea bass	65.3 ± 5.7	6 wk	25	Enhanced lysozyme antibacterial activity and serum trypsin inhibition linked to the anti-parasite activity of the fish.	Henry et al. (2018)
	Meal	Rainbow trout	105.2 ± 0.17	163 d	50	Reduction in some essential amino acids (Ala, Ile, Leu, and Lys).	Iaconisi et al. (2019)
	Meal	Rainbow trout	1.11 ± 0.01	8 wk	14	Improved growth performance and lysozyme activities	Jeong et al. (2020)
	Meal	Baltic prawn (<i>P. adspersu</i>)	0.49 ± 0.1	60 d	18	Higher protein and energy contents in the muscles	Mastoraki et al. (2020)
	Meal	Siberian sturgeon	640 ± 3.9	60 d	15	Increased thickness of the muscular layer in the gastrointestinal tract and decreased the total number of bacteria	Józefiak et al. (2019b)
	Partially defatted	Rainbow trout	78.3 ± 6.24	22 wk	100	Slight modulation observed in the gut and skin microbiota by reducing pathogenic bacteria count	Terova et al. (2021)

(continued on next page)

Table 2 (continued)

Insect species	Used part	Aquaculture species	Fish weight, g	Period	Inclusion level, %	Effect	References
	Meal	Mandarin fish (<i>Siniperca scherzeri</i>)	20.8 ± 0.05	8 wk	30	Improved growth and feed efficiency and enhanced serum lysozyme and glutathione peroxidase (GPx) activities.	Sankian et al. (2018)
	Meal	Yellow catfish (<i>Pelteobagrus fulvidraco</i>)	10.0 ± 0.03	5 wk	18	Enhanced immune response and disease resistance against <i>Edwardsiella ictaluri</i>	Su et al. (2017)
	Meal	Rainbow trout	53.4 ± 3.74	71 d	20	Improved growth performance, reduced villus height and increased count of beneficial bacteria in the intestine	Józefiak et al. (2019a)
	Meal	White shrimp	2.39 ± 0.49	8 wk	100	Enhanced the weight gain, specific growth rate and feed conversion rate	Choi et al. (2018)
	Meal	Narrow-clawed crayfish (<i>Pontastacus leptodactylus</i>)	0.011 ± 0.002	80 d	50	Improved weight gain, specific growth rate, protein efficiency ratio, apparent net protein utilization, molting frequency, and feed conservation ratio, but lower survival rate as compared to the other diet groups. Also improved protein and lipid content of the whole body	Mazlum et al. (2021)
	Meal	Black porgy, (<i>Acanthopagrus schlegelii</i>)	6.43 ± 0.00	12 wk	60	Improved serum lysozyme activity and upregulation of antioxidant enzyme-related genes but with declined fillet lipid content	Jeong et al. (2022)
Superworm larvae (<i>Zophobas morio</i>)	Meal	Nile tilapia	3.00 ± 0.2	12 wk	15	Enhanced innate immune parameters (thrombocytes and neutrophils), liver and serum lysozyme activity, and complement system activity	Alves et al. (2021)
Housefly (<i>Musca domestica</i>)	Meal	Baltic prawn (<i>P. adspersu</i>)	0.49 ± 0.1	60 d	18	Enhanced growth performance but lowered survival	Mastoraki et al. (2020)
Cricket (<i>Gryllus bimaculatus</i>)	Meal	African catfish	13.2 ± 0.3	7 wk	100	Improved growth performance, haemoglobin, haematocrit and catalase activity	Taufek et al. (2016)
Tropical house cricket (<i>Grylodes sigillatus</i>)	Meal	Rainbow trout	53.4 ± 3.74	71 d	20	Lowered growth performance, reduced villus height and increased count of beneficial bacteria in the intestine	Józefiak et al. (2019a)
Turkestan cockroach (<i>Blatta lateralis</i>)	Meal	Rainbow trout	53.4 ± 3.74	71 d	20	Improved growth performance, increased villus height and count of beneficial bacteria in the intestine	Józefiak et al. (2019a)

the fish (Fawole et al., 2020). In rainbow trout, Elia et al. (2018), reported that dietary inclusion of at least 20% BSF could adversely affect the fish's oxidative homeostasis, particularly in the liver and kidney by lowering the glutathione peroxidase (GPx) activity while enhancing the activities of ethoxyresorufin O-deethylase (EROD), glutathione S-transferase (GST) and total glutathione (GSH). Therefore, the authors suggested adding levels of BSF that are lower than 20% in the fish's diets. In Atlantic salmon, increasing the levels of BSF paste from 6.25% to 25% in fishmeal and plant-based diets improved the antioxidant capacity in the blood of the fish (Weththasinghe et al., 2021). In Pacific white shrimp, dietary replacement of fishmeal with defatted silkworm (SW) (*B. mori* L.) pupae meal enhanced the serum antioxidant capacity of the shrimp (Rahimnejad et al., 2019). Recently, Xu et al. (2020a) reported the effect of insect oils on the antioxidant status of juvenile mirror carp (*C. carpio* var. *specularis*). In this study, the combined inclusion of BSF oil, silkworm pupae oil and TM oil at the same level improved the antioxidant capacity in the liver of the fish. When individual insect oils were compared, the authors observed that BSF oil could provide better results compared to the other two oils. Furthermore, Xu et al. (2020b) reported significantly improved serum antioxidant capacity in mirror carp fed dietary BSF pulp at low levels. Other insect meal proteins that have shown similar results include cricket (*Gryllus bimaculatus*) meal in the diet of African catfish (Taufek et al., 2016) and maggot meal in the diet of common carp (Ogunji et al., 2011). Dietary inclusion of TM in the diet of rainbow trout improved the intestinal antioxidant enzyme activity and led to a decline in lipid peroxidation (Henry et al., 2018). The antioxidant capacity of the hybrid tilapia was not affected when the fish was fed a diet containing maggot meal as a full replacement for fishmeal (Qiao et al., 2019).

4.2.3. Immune response and disease resistance

The response of immune function in aquatic animals to dietary supplementation has become an important criterion for evaluating the suitability of feed ingredients in aquaculture. Insect utilization in aquafeed has been evaluated on several immune-related parameters including blood biochemical composition, histopathology of related organs, gut health, related gene expression and disease resistance in numerous aquaculture species. The results of these parameters are included in Table 2. In Atlantic salmon diets, full fishmeal replacement with BSF meal could be achieved without negative effects on liver histology and the transcription of pro-inflammatory genes in the fish's head kidney (Belghit et al., 2019; Stenberg et al., 2019). In juvenile Japanese seabass, dietary BSF meal supplementation did not alter the intestinal histomorphology of the fish (Wang et al., 2019). The substitution of fish meal with BSF meal in the diets of the African catfish did not alter the fish's blood biochemical parameters and differential leucocyte counts (Fawole et al., 2020). Also, no significant effect was observed on the gut histology, stress levels, and immune response in zebrafish when fishmeal was replaced by BSF at 25% and 50% (Zarantoniello et al., 2019). In juvenile Japanese seabass (*L. japonicus*), partial replacement of fishmeal up to 64% with defatted BSF larvae meal did not affect the histomorphology of the intestine and liver, or intestinal antioxidant status and immune response of the fish (Wang et al., 2019). However, replacing fishmeal with TM in the diets of juvenile Pacific white shrimp improved the survival rates of the shrimp after being challenged with pathogenic bacteria (*Vibrio parahaemolyticus*) (Motte et al., 2019). In yellow catfish, dietary TM at 18% could improve the immune response and disease resistance of the fish against a bacterial (*Edwardsiella ictalurid*) challenge (Su et al., 2017). In juvenile mandarin fish, the inclusion of TM in the diets could enhance the immune system of the fish (Sankian et al., 2018). In Siberian sturgeon, BSF meal enhanced the morphology of

the intestine, although higher inclusion levels of more than 18.5% were likely to negatively impact the health status (Józefiak et al., 2019a; Caimi et al., 2020b). Interestingly, the resistance of Pacific white shrimp against *V. parahaemolyticus* and stress was not affected after feeding the shrimp with BSF meal (Richardson et al., 2021). In zebrafish grown from larvae to adult, fishmeal could be replaced by 25% and 50% BSF meal without adversely affecting the immune response and stress resistance of the fish (Zarantoniello et al., 2019). The health status of the African catfish was not negatively affected when fishmeal was replaced by 75% (Fawole et al., 2020). In giant freshwater prawn (*M. rosenbergii*), replacing fishmeal with TM at 12% improved immune response and the resistance of the prawn against *Lactococcus garvieae* and *Aeromonas hydrophila* (Feng et al., 2019). Existing studies show slight variations with regard to the insect species and meal status used in aquafeed. For example, replacing fishmeal with a 50% partially-defatted BSF meal did not yield a significant effect on the histology of the spleen, liver and gut of rainbow trout (Elia et al., 2018). While 28% to 67% full-fat TM meal as a replacement for fishmeal could improve the immune response in the fish (Henry et al., 2018; Jeong et al., 2020). In Nile tilapia, a total replacement of fishmeal was achieved using BSF meal with observed improvement in the haematology and immunity of the skin mucus (Tippayadara et al., 2021), while only 15% could be replaced with superworm (SW) larvae (*Z. morio*) for enhanced innate immunity of the fish (Alves et al., 2021). Few studies have also reported the combined effect of multiple species of insect meals in aquaculture (Józefiak et al., 2019b), but further investigations are required.

In Pacific white shrimp, dietary replacement of fishmeal with defatted silkworm pupae meal at higher (over 75%) levels could have adverse effects on the integrity of the hepatopancreas in the shrimp (Rahimnejad et al., 2019). In the findings of Motte et al. (2019), replacing fishmeal with 50% defatted TM improved the disease resistance of the Pacific white shrimp against EMS (*V. parahaemolyticus*). In rainbow trout, Bruni et al. (2018) reported the effect of replacing fishmeal with partially defatted BSF meal on the intestinal microbial community of the fish. In this study, the authors concluded that 50% of BSF meal in the diets could improve biodiversity and modify the microbial community structure in the intestine of rainbow trout. In red seabream (*Pargus major*), feeding the fish with diets containing TM after challenge with a bacterial pathogen (*Edwardsiella tarda*) improved the fish's survival (Ido et al., 2019).

The utilization of insect meals in aquaculture could promote the use of plant-based protein, particularly soybean meal whose application in the culture of high-value species has declined because it causes intestinal enteritis. In rainbow trout, the inclusion of BSF meal in soybean meal-based diets successfully prevented soybean meal-induced intestinal enteritis (Kumar et al., 2021). This was accompanied by down-regulated prostaglandin and interferon regulatory factor 1 (IRF-1) in the fish's intestine. However, the mechanism through which insect meal prevents soybean meal-induced enteritis in fish is not clearly understood. According to Xiang et al. (2020), insect meal contains bioactive peptides that could be attributed to the prevention of this disease. Therefore, insect meal presents the potential prevention of intestinal inflammation in aquaculture. However, as observed by Kumar et al. (2021), this requires further investigation to characterize the bioactive peptides present in insect meals.

In some aquaculture species, the component of the insect used in the diet could yield different results. Furthermore, different organs of aquatic animals could respond differently to varying levels of insect meal included in the diets. For example, in the diets of Atlantic salmon, the inclusion of 6.25% and 12.5% of BSF meal in fishmeal and plant-based diets could reduce the enterocyte

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

4.2.4. Effect of insect meal on fish flesh quality and safety

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

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

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

4.2.5. Consumer opinion on the consumption of aquaculture products fed with insect meal

The use of insects as feed ingredients in aquaculture is a relatively new but highly promising technology for mitigating the rising cost of aquafeed due to sustainability issues of fishmeal (Baldi et al., 2021; Hasimuna et al., 2019; Kord et al., 2022). However, the wider adoption of insect utilization in aquafeed will likely depend, to a larger extent, on aquaculture producers and consumer acceptance. Despite few existing studies investigating people's perception concerning the use of insects as feed ingredients, the majority of the aquatic animal product consumers have shown favourable responses for various reasons, including risk-free (Popoff et al., 2017; Szendrő et al., 2020), sustainability considerations (Verbeke et al., 2015; Rumbos et al., 2021), as well as availability and access to information about the products (Baldi et al., 2021; Rumbos et al., 2021). Product awareness and information availability are considered the most important factors that could accelerate the acceptance and positive perception of aquatic products produced on insects-based feeds (Baldi et al., 2021; Rumbos et al., 2021). According to Baldi et al. (2021) reducing information asymmetry could promote wider consumer acceptance. Interestingly, a study conducted in Italy revealed that men and young consumers are more likely to accept aquatic products given insect-based feeds (Baldi et al., 2021), suggesting that gender and age could play a role. Further, the authors observed that well-informed respondents had a higher acceptance rate compared with those that had little to no information. Sogari et al. (2019) also noted that, in Australia, males were more likely to accept insect products as food compared with their female counterparts. However, in Belgium, age and gender did not appear to significantly affect the perception of the aquatic products. As observed by Verbeke (2015), consumer perception regarding insect use in aquafeed is likely to evolve with time and

vary based on culture, familiarity and past experiences, meaning that acceptance of aquatic products fed insect-based diets will improve with accumulation of information about the product. Additionally, different cultures and beliefs are likely to affect perception although further studies are required to confirm it. Currently, the majority of existing studies were conducted in developed countries, particularly the European Union (EU), with no current information for developing countries. This lack of information makes it difficult to predict perception in developing countries and among different social groups. Therefore, more studies are required in different countries, at least the major producers, and among consumers from different cultures to ascertain the future of insect utilization in aquafeed.

5. Conclusion

Insects have emerged as a potentially sustainable alternative protein source to the conventional fishmeal whose production continues to be unsustainable, resulting in rising costs. Significant progress has so far been made in the efforts to unlock the potential of insects for use in aquafeed. Our review of existing studies in this area has shown promising results, particularly with regards to enhanced growth performance, nutrient utilization, antioxidant capacity, immune response as well as disease resistance in many aquaculture species. Mechanisms have also been identified to enrich the nutritional value of insects, making them more effective as an aquafeed ingredient. Besides, the low carbon footprint associated with their production makes them an even more interesting protein source candidate in aquafeed. However, there are still many areas that require further investigation to fully understand the utilization and benefits of insects in aquafeed.

6. Prospects

Despite the promising results reported from the inclusion of insects as ingredients in aquafeed, important gaps still exist concerning their full utilization in aquaculture. For example, the majority of effects of insect utilization in aquafeed reported so far have important biases towards adult species. A large gap still exists with regards to the effects in the initial ontogenetic stages of fish such as embryos, fingerling and larvae. Additionally, the insect requirement levels in aquafeed for different aquatic animal species and stages of development under different culture systems are unclear. This knowledge is very important for commercializing the utilization of insects in aquafeed. Also, given the numerous insect species currently reported as ingredients in aquafeed, there is a need to explore value addition methods during biomass production to improve the nutritional value. This will ensure the diets are easily utilized by the aquatic animals while reducing waste in culture facilities. Emerging studies show that different parts of insects such as meal, oil, pulp and paste can be used in aquafeed. However, the majority of studies in the literature have focused on insect meals to a larger extent and oils to a lesser extent, while very little is known regarding the utilization of pulp and paste. Furthermore, important bioactive compounds such as chitin, fatty acids and antimicrobial peptides have been reported in insects, however, their role in aquatic animal growth and physiology is not very clear. Besides, chitin has shown detrimental effects at higher insect inclusion levels in the diets of aquatic animals. Future studies are required to explore how different parts and compounds of insects could be utilized in aquafeed. Finally, studies evaluating the effect of insects on flesh safety and quality of fish and other aquatic food for human consumption are necessary. Addressing these gaps is relevant for the commercialization of insect utilization in aquafeed.

Author contributions

Sahya Maulu conceptualized the study, developed the objectives and coordinated the manuscript writing, **Sandra Langi, Dag-oudo Missinhoun, Oliver Jolezya Hasimuna, Buumba Hampuwu, Brian Pelekelo Munganga, Ndakalimwe Naftal Gabriel, Mabrouk Elsabagh, Hien Van Doan, Zulhisyam Abdul Kari, and Mahmoud A.O. Dawood** wrote the draft manuscript. All the authors reviewed the final manuscript draft and approved its submission for publication consideration.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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