Iranian Journal of Fisheries Sciences 22(6) 1228-1264 2023
DOI: 10.22092/ijfs.2024.130761

Review Article

Sensory and quality properties of aquaculture products influenced by insect-based and aquatic-origin diets: A review

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Received: September 2023 Accepted: October 2023

Abstract

Aquaculture plays a critic role in food security and supplying healthy foods. Replacing fishmeal and soybeans with new protein ingredients such as insect- and aquatic-based dietary compounds to reduce breeding costs is one of the priorities of the aquaculture industry. These new compounds are valuable sources of proteins, amino acids, fatty acids, vitamins, and minerals that can be used in aquatic nutrition. This article systematically reviews the effects of using these compounds on the quality and sensory properties of aquaculture products. The review of sources shows that the excessive application of these ingredients in the diet of farmed aquatic animals has a significant influence on their quality and sensory characteristics. Therefore, it is necessary to conduct a systematic review of published scientific sources in order to achieve reliable results. This study also highlights the importance of using quality and sensory analysis of aquacultured products when using new nutritional sources and provides practical information for aquaculture stakeholders, especially fish nutritionists.

Keywords: Fish feed, Insects, Fishmeal, Seafood quality, Sensory evaluation

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Introduction

The demand for seafood is increasing due to the rapid growth of the human population and the increase in living standards. Therefore, with the reduction of access to wild fish and crustaceans, in the coming decades, aquaculture will be a very important source of providing high-quality proteins for humans (Daniel, 2018; Stankus, 2021).

Aquaculture production accounts for about 50% of all seafood for human consumption in 2022 and it is expected to increase in the coming years due to the importance of preserving marine aquatic stocks and providing the protein needs of the growing world population. Aquaculture is highly dependent on a continuous supply of fishmeal, which is the most important element in commercial aquafeed. However, the price of fishmeal has increased in recent decades due to various reasons, including competition with other animal proteins, the lack of global supply of fishmeal, and the increase in demand. Therefore, aquaculture has put increasing pressure on fish industry to supply fishmeal, which has led to a rapid decrease in wild fish stocks (Stankus, 2021). With the increase in aquaculture costs, including fishmeal, corn, and soybean meal, which account for 60-70% of the total cost of production, further development of aquaculture has faced limitations. By 2025, more than 35 million tons of aquatic food will be needed. Therefore, it is not possible to use more fishmeal and oil in aquaculture, and alternative protein sources will be needed. In the next 2 decades, the aquaculture industry will rely on fishery and aquaculture wastes and insect protein in addition to vegetable proteins to supply the protein needed by aquatic animals. Therefore, alternative protein sources those have similar nutritional benefits to fishmeal have been widely studied. Insect meal or protein and protein products obtained from fish by-products, such as fish protein hydrolysis and fish silage, are products that are sustainable alternatives to conventional animal proteins like fishmeal in animal farming (Daniel, 2018; Gasco *et al.*, 2020a). Therefore, looking for alternatives to fishmeal in aquaculture feed industry is considered as a global research priority (Luthada-Raswiswi *et al.*, 2021; Alfiko *et al.*, 2022). Accordingly, several systematic reviews or meta-analyses on animal protein sources as a substitute for fishmeal in aquaculture diets have been published recently (Sánchez-Muros *et al.*, 2014; Henry *et al.*, 2015; de Souza-Vilela *et al.*, 2019; Gasco *et al.*, 2018; 2019; 2020b; Nogales-M´erida *et al.*, 2019; Sogari *et al.*, 2019; van Huis 2020; Luthada-Raswiswi *et al.*, 2021; Liland *et al.*, 2021; Lähteenmäki-Uutela *et al.*, 2021; Alfiko *et al.*, 2022; Lee *et al.*, 2022). Comprehensive studies that assessed animal protein sources as a fishmeal replacement in fish diets in aquaculture and its influence on aquatic performance, weight, specific growth rate, feed conversion, and survival rates were provided by them.

The results of the last two decades' research indicate that these ingredients can replace a part of fish protein in the diet of aquatic animals, but excessive use can have negative effects on the growth of aquatic animals (de Souza-Vilela *et al.*, 2019; Liland *et al.*, 2021). However, it should be ensured that the use of these new ingredients in the aquatic diet does not have a negative effect on the quality of the aquatic meat. Because of these ingredients may affect the consumer's preferences and sensory marketing. Contradictory results have been reported regarding the use of insect-based products (IB) or aquaculture-origin (AO) diets on quality and sensory characteristics of aquaculture products (Nandeesha *et al.*, 2000, 1998; Sealey *et al.*, 2011; Lock *et al.*, 2016; Stadtlander *et al.*, 2017; Borgogno *et al.*, 2017; Belghit *et al.*, 2019; Bae *et al.*, 2019; Turek *et al.*, 2020). For this reason, there is a need to evaluate sensory characteristics and quality parameters so as not to damage the market of these products.

The nutritional value of a food is very important in its acceptance, but the priority of purchasing and continuous consumption of the product depends on its sensory quality (Meilgaard *et al.*, 2015). Products of AO that are used as animal feed have the odor and taste of fish and seaweed, bitterness, sourness, etc. Insects have unique sensory characteristics, such as the odor and flavor of peas in mealworm meal (Shaviklo *et al.*, 2021a) or the odor of plants, beans, fruits, and nuts in silkworms (Mishyna *et al.*, 2020), which should be considered in animal nutrition. Livestock feed may affect the sensory quality of farmed livestock products, and in this context, it is necessary to know the effect of feed on the sensory characteristics of aquaculture products. Providing such data is necessary before introducing feed products to the market or when using new materials in livestock breeding (Shaviklo *et al.*, 2021a). On the other hand, it is necessary to know whether the use of these more sustainable feed sources may increase the consumer's willingness to pay for aquaculture products fed with these new protein sources (Shaviklo *et al.*, 2021b). This study was conducted with the aim of comprehensively reviewing and collecting published information regarding the impact of IB and AO products on the quality and sensory properties of aquaculture products fed with these compounds.

Methodology and research design

The umbrella review methodology was adapted from Cant *et al.* (2022). Accordingly, the modified methodology consisted following steps:

a) *Review justification:* There is a scientific need to know the influence of incorporating IB and or AO products on the sensory and quality properties of aquaculture products.
b) *Designing the study*: The study was designed based on an umbrella methodology.
c) *Preparing the search strategy and conducting the literature search:* The strategy of this research was to collect and review the literature and draw practical conclusions from the studies. The Google Scholar database was searched for all published texts

on the research topic from 1960 to 2023 and relevant articles were collected.

d) *Identifying relevant results:* The collected articles were screened and only the articles that studied the effect of IB and or AO on the quality and sensory characteristics of the aquaculture product were selected for review.

e) *Reporting findings and evidence summary:* The research method and results of each article were summarized. Accordingly, they were critically and impartially analyzed.

f) *Reporting review limitations:* There were no limitations to the implementation of this study.

g) *Conclusion:* The incorporation of IB and or AO products in aquafeed and their influence on sensory and quality attributes of aquaculture products were described. In the last 3 decades, more than 1000 articles published in English have discussed the use of various IB and or AO products in aquaculture (googlescholar.com). More than 95% of these articles have dealt with the effect of this new source on growth performance and safety and issues related to aquatic growth physiology. Less than 5% of published articles were focused on quality issues and the impact of these sources on aquatic sensory characteristics. Therefore, there is a big gap in this regard that needs to be addressed. Because the commercial production of IB and or AO products and the development of their use in aquaculture will strongly depend on its effects on the quality of farmed aquatic meat. Accordingly, a summary of the most reliable published results was prepared and presented. The protein/oil supplements, the inclusion levels, aquatic species, farming period, quality, and sensory assessment methods were included in the table to help readers to follow the results.

Quality and sensory attributes of aquaculture products

In general, fish meat contains approximately 18% protein, about 80% moisture in low-fat species, and 74-80% in high-fat species and the amount of fat varies from a few percent to more than 20%. Minerals and vitamins make up a smaller amount of the chemical composition of fish meat (Espe, 2008).

Unfortunately, fish quality is one of the most misused words in aquaculture research. Quality in fresh seafood is a meaningful concept that includes various physicochemical, microbiological, and sensory characteristics that can be measured directly or indirectly. Therefore, the freshness of fish can be considered a combination of different nutritional and sensory characteristics (Hardy and Lee, 2010; Hicks, 2016).

Many factors affect the quality of farmed and wild aquatic animals. Seasonal changes, variations in the amount of energy in the diet, the manipulation of diet compositions, and light regimes that lead to the change in the breeding condition are factors that may affect the nutritional and sensory quality of farmed aquatic meat (Espe, 2008). On the other hand, the chemical composition of aquatic animals depends on many factors such as species, size, age, gender, fat content, the salinity of the water of the breeding/ growing place, fish feed, fishing time, geographical region, and temperature of the water of the breeding/ growing place (Kong *et al.*, 2020).

Although most of the qualitative characteristics of both groups of aquatic animals are the same, many of these traits can be controlled under farmed conditions, while their control in wild fish is beyond our control. Wild aquatic animals do not have uniform nutrition throughout their life and experience periods of abundance and scarcity of feed as well as diversity in the type of feed, while farmed aquatic animals are fed using feed provided by breeders during the breeding period. Therefore, aquafeed is a critical factor that affects the quality of aquaculture products (García *et al.*, 2022). However, this is a potential advantage for farmed aquatics over wild aquatics, an advantage that the aquaculture industry has been slow to exploit (Hardy and Lee, 2010; Hicks, 2016).

Apart from the nutritional value of new feed ingredients, their effects on the quality of the cultured product are very important. The training of panel members significantly affects their ability to understand sensory differences and it is necessary to develop training programs for them (Shaviklo *et al.*, 2021b). Using vocabulary list for sensory evaluation of the samples will help the panelists to evaluate aquaculture products perciesly. Tables 1 and 2 provided sensory lexicon for sensory analysis of cooked fish fillet and or cooked shrimp.

Table 1: Consensus list for sensory evaluation of cooked fish fillet (adapted from Borgogno *et al.*, 2018).

Sensory attribute	Scale (0-9)	Definitions
Texture		
Tenderness	E. weak | E. strong	Minimum force required to chew the fish samples: the lower the force the higher the tenderness
Juiciness	E. weak | E. strong	Moisture released by the product in the mouth during early chewing
Fibrousness	E. weak | E. strong	Perception of long and coarse particles in the meat during the chewing
Melt in mouth	E. weak | E. strong	The ability of the sample to dissolve into the mouth
Taste		
Sweet	E. weak | E. strong	Basic taste sensation generated by sugars
Salty	E. weak | E. strong	Basic taste sensation generated by salts
Bitter	E. weak | E. strong	Basic taste sensation generated by caffeine or quinine
Umami	E. weak | E. strong	Basic taste sensation generated by certain peptides and nucleotides
Odor and flavor		
Fresh fish	E. weak | E. strong	Odors and flavors related to fresh fish
Boiled fish	E. weak | E. strong	Odors and flavors related to boiled fish
Juiciness	E. weak | E. strong	How juicy is the sample up to the fourth chewing?
Algae	E. weak | E. strong	The characteristic aroma associated with green notes, like algae

Table 1 (continued):

Sensory attribute	**Scale (0-9)**	**Definitions**
Metallic	E. weak | E. strong	The flavor associated with various metal flavors found in fish
Overall aroma	E. weak | E. strong	The total strength of olfactory sensation
Overall flavour	E. weak | E. strong	The total strength of taste and flavoring sensation in the mouth
Mouthfeel		
Astringency	E. weak | E. strong	Dryness of the oral surface and tightening and puckering sensation of mucosa and muscles around the mouth

E: extremely.

Table 2: Sensory lexicon defined by Erickson *et al.* (2007) for sensory analysis of cooked shrimp.

Attributes	**Definition**
Odor	
Ocean/seawater	The odor associated with ocean/ seaweed.
Cooked shrimp	The odor associated with freshly cooked shrimp.
Old shrimp	The odor associated with stored cooked shrimp.
Flavor	
Cooked shrimp	The flavor associated with cooked shrimp
Tastes	
Bitter	The intensity of the taste associated with caffeine solutions.
Salty	The intensity of the taste associated with salt solutions.
Sour	The intensity of the taste associated with citric acid solutions.
Sweet	The intensity of the taste associated with sugar solutions.
Mouthfeel	
Sliminess	The feeling of a slimy film in the mouth.
Texture	
Firmness	The amount of force required to bite the end of the cooked shrimp tail and cut it using the molars and then chew it.
Juiciness	The amount of moisture in cooked shrimp meat makes it easy to chew and swallow.
Chewiness	The time required to masticate the sample to a consistent acceptance for swallowing.
Fibrous	The presence of individual muscle fibers in shrimp meat.
After taste	
Iodine	Aftertaste associated with the chemical iodine.

The fact that the diet of farmed fish significantly affects the nutritional value and sensory quality of fish meat has already been studied (de Francesco *et al.*, 2007; García-Romero *et al.*, 2014a). The quality properties and sensory characteristics of aquatic products fed IB and AO products may be changed because the use of these components may lead to significant changes in the fatty acid composition of fish fillets (Borgogno *et al.*, 2017). On the other hand, the quality of fillet or meat of aquaculture products is a combination of nutritional value and sensory characteristics (Grigourakis, 2007), both of which are closely related to dietary composition. The quality of aquaculture products affects the purchasing behavior of consumers and causes the success or failure of the seafood industry (Hardy and Lee, 2010).

As mentioned earlier, dietary fats can change the quality of fillets and meats (especially their taste and flavor). Skin and fillet color, texture, taste, odor, and acceptance of fish are evaluated as part of the quality control of farmed fish. It should be kept in mind that consumers' sensory attributes differ in different cultures. These attributes may be changed by changing the feed formula. The texture of fish meat cannot be easily changed, but it has been reported that the addition of algae supplements to fish feed improves the texture of cultured fish meat (Nakagawa and Montgomery, 2007). The flavor of farmed fishery products can rarely be improved by dietary changes. But the odor of these products is affected by the diet and it affects the flavor of the product. Some food items have been proven to change the farmed ffish’s odor and flavor. For example, if fish oil is consumed in excess of the desired amount, fish meat acquires a strong fishy odor (Dupree *et al.*, 1979).

It is reported that fish fed a vegetable protein-based diet were sweeter and less odorous than the control fed a fishmeal-based diet (De Francesco *et al.*, 2004). The amount of protein in a particular aquatic species is relatively constant and varies little with aquatic size. Feed composition has little effect on fish muscle protein content. Amino acid content is more or less constant in aquatic meat because the main proteins in muscle, actin, and myosin, have constant amino acid compositions. Therefore, the amount of protein or the amino acid profile in farmed fishery products cannot be modified by diet (Iaconisi *et al.* 2019). It has been reported that the meat quality of aquaculture species can be changed by feed. For example, red tilapia will gain more weight if fed a feed with a higher protein content (Santos *et al.*, 2014). Rainbow trout fillets fed a high-fat diet, had a more tender texture (Lie, 2001).

The amount of fat and the ratio of fatty acids of farmed aquatic animals depends on the diet and they can be changed with the ingredients of the diet. The fatty acid profile of farmed fish reflects the fatty acid profile of the diet. Therefore, it can be changed by changing the source of fat in the diet, but this depends on the amount of dietary fat consumed in a certain period of time. The content of unsaturated fatty acid (UFA) in fillets is one of the indicators affecting the quality of seafood. Therefore, it is very important that farmed fish products contain levels of n-6 polyunsaturated fatty acids (PUFA) that meet consumer expectations (Bell *et al.*, 2001). Fat is mainly responsible for the flavor of food and therefore, it is important to know the sensory properties that fatty acids may produce (Stadtlander *et al.*, 2017).

On the other hand, changes in the fat and fatty acid composition of farmed fish meat directly affect the total volatile compounds and affect the odor and flavor of the fish (Turchini *et al.*, 2003). Substitution of fishmeal with insect meal can increase the fat content or change the nature of lipids in fish and thus can change the fish fillet flavour (Bundary and Shepherd, 1981). The fatty acid profile of insects varies greatly depending on the insect species and the substrates used for their rearing (Biancarosa *et al.*, 2018; Meneguz *et al.*, 2018; Gasco *et al.,* 2018), which in turn can affect the fatty acid profile of cultured aquatic animals. The lipid profile of insect larvae is rich in saturated fatty acids and poor in polyunsaturated fatty acids (eicosapentaenoic acid, EPA, and docosahexaenoic acid, DHA). Fats affect the sensory characteristics of food; therefore, they play an important role in quality control (Sikorski and Kalakowska, 2002). For this reason, the fillet and meat of cultured aquatic animals are often used for quality assessment in terms of fat content and quality and characteristics of fatty acids.

Color is a very important sensory attribute in products such as salmon and trout fillets. In addition, the color of the skin of some aquatic species is an important characteristic that determines the market value and can significantly affect the acceptance of aquatic products (Li *et al.,* 2016). Color in fish comes from the deposition of carotenoid pigments in the skin and flesh. Carotenoid sources used in aquaculture feed may be provided from natural sources like shrimp or krillmeal, seaweed or yeast, or from industrial products. The recomended level of carotenoid pigment in salmon fillets is ≥4 μg/g wet tissue. This level of pigmentation is acceptable to consumers (Turck *et al.,* 2022).

The color of the skin and flesh of aquculture products can be affected by the diet characteristics (García-Romero *et al.,* 2014a; Tibaldi *et al.,* 2015). The presence of different pigments in the diet composition can lead to an increase in fish skin pigmentation (Belli *et al.,* 1996; Walker and Berlinsky, 2011; Tulli *et al.,* 2012).

The level of some vitamins can be increased in the tissue of farmed fish by using feed supplements. The amount of ascorbic acid and fat-soluble vitamins in farmed fish meat can be increased with a proper diet. The level of water-soluble vitamins, with the exception of ascorbic acid, can be increased less in farmed fish meat using food supplements, and excess amounts are simply excreted from the body. The amount of essential minerals, such as calcium, phosphorus, zinc, etc., is maintained within the physiological range required in all animals, and the level of minerals in cultured fish cannot be increased by feed supplements.

The pH is an important index in quality assessment of fish fillets and is considered as an indicator of fish freshness (Cortes-Ruiz *et al.,* 2001). It is documented that blackspot seabream fillets fed a diet containing 50% fishmeal replaced with high-fat yellow mealworm larvae had a lower pH value (Iaconisi *et al.,* 2017). In another report, no significant change in pH value was observed in rainbow trout fillets fed with up to 25% high-fat yellow mealworm larvae compared to the control (Iaconisi *et al.,* 2018).

Post-mortem glycolysis causes the cumulation of lactic acid in the muscles, thereby lowering the pH value of the muscles. Therefore, the significant increase of lactic acid in fish fillet and the decrease of pH value after harvest is related to the higher activities of anaerobic glycolysis before death, and this is considered as a good index of the initial stress of fish before catching (Poli *et al.*, 2005). Iaconisi *et al.* (2018) stated that 50% replacement of dietary fishmeal with yellow mealworm in blackspot seabream caused high stress, which led to a decrease in the pH value of fish fillets. Therefore, they suggested that no more than 25% of fishmeal replacement should be included with yellow mealworm in the diet of blackspot seabream.

Insects are good sources of pigments, especially β-carotene. This red color substance is one of the carotenoids (Finke, 2002). Carotenoids intensify the red color of fish skin (Iaconisi *et al.*, 2017). Carotenoids are accumulated in fish skin and flesh (Hardy, 2002) and since fish are unable to resynthesize this componets, their presence in fish tissue is closely related to dietary supplements.

Sensory and quality charcteristics of aquaculture products affected by IB and AO diets

There is few reports on influence of feeding IB and AO diets on the sensory and quality of aquaculture products published in the last 6 decades. Many authors did not correctly determine the quality and sensory characteristics of the examined samples. Therefore, among the limited number of articles obtained in this regard, only a few of them can be mentioned. The results of these researches were summarized in Table 3.

The IB products

Insects are natural food sources for animals, especially for fish that require relatively high proteins in their diet (Nogales-Merida *et al.*, 2019; Tran *et al.*, 2015; van Huis, 2020). In the last 4 decades, the use of insects in aquaculture began, and during these years, incredible advances in species selection, cultivation, production maximization, nutritional values, and field trials for the use of this food source in aquaculture have been reported (Daniel, 2018).

So far, more than 15 insect species have been used and tested for alternative protein sources in aquatic animals (Alfiko *et al.*, 2022). Among them, the following seven species (Fig. 1) were permitted by EU regulation (European Union, 2017) for application in aquaculture as cited by Lähteenmäki-Uutela *et al.* (2021) and Lee *et al.* (2022).

a. Banded cricket (*Gryllodes sigillatus*)
b. Black soldier fly (*Hermetia illucens*)
c. House cricket (*Acheta domesticus*)
d. House fly (*Musca domestica*)
e. field cricket (*Gryllus assimilis*)
f. Lesser mealworm (*Alphitobius diaperinus*)
g. Yellow mealworm (*Tenebrio molitor*)

Biological and farming methods (Tran *et al.*, 2015; Gasco *et al.*, 2018) and proximate analysis and/or nutritional values were already documented by Sanchez-Muros *et al.* (2014); Henry *et al.* (2015); Allegretti *et al.* (2017); and de Souza-Vilela *et al.* (2019).

Table 3: Summary of published research in the recent decades reporting the effect of IB and AO products on sensory attributes of aquaculture products.

No.	Type of ingredient	Methods and results
1	Black soldier fly (*Hermetia illucens*) larvae meal Ref. Belghit *et al.*, 2019	**Inclusion levels**: 33%, 66%, and 100% of the fishmeal **Aquatic Species:** Atlantic salmon (*Salmo salar*) **Farming period:** 128 days **Feeding days:** 114 days **Quality assessment: -** **Sensory analysis:** Liking tests using a 15 cm line-scale **Number of assessors:** 10 trained assessors with an average of 15 years of experience in sensory analysis. **Test sample:** fish fillet **Sample preparation:** The middle of the fillet was divided into 3×3 cm pieces. Skin and bones were removed. The samples were vacuum packed and frozen at -40°C and stored for 2 months. Defrosting was done at 0-1°C. Cooking in the oven was done at 75°C until the center temperature reached 59°C. Raw and heated samples were served in white plastic containers with lids at a temperature of 20 °C. **Results:** Olfactory evaluation showed that there is a significant difference between the treatments. Cooked salmon with 100% fishmeal replacement with BSF larvae meal had a higher score for rancid odor compared to the control treatment. The rancid odor of raw salmon and the off-odor of cooked salmon showed the same tendency. There were no significant flavor differences between treatments, but scores for the rancid flavor of cooked fillets increased with increasing levels of dietary BSF larvae meal inclusion. No significant difference was observed for the salmon color score between treatments, but the color intensity of cooked salmon in the sample containing 66% IM was significantly lower compared to the control. Raw salmon fed 100% BSF larvae meal was tenderer compared to the treatment that received 33% BSF larvae meal, while an opposite trend was observed for cooked salmon, where salmon fed a higher volume of BSF larvae meal it tended to be stiffer. A higher drip loss was detected in raw salmon fed the 66% BSF larvae meal diet compared to the control. No significant relationship was observed between the level of inclusion of insect meal in the diet and any of the sensory characteristics.
2	House crickets (*Acheta domesticus*) and live super worm (*Zophobas morio*) larvae Ref. Turek *et al.*, 2020	**Inclusion levels**: The control group (C) received commercial pellets only. For other groups, 25% of the crude energy of pellets was replaced with live adult house crickets (H), live super worms' larvae (S), or a combination of 12.5% crude: gross energy of each of the insect species (HS). The insect-only group (I) was fed live crickets and super worms only (50:50 crude energy). **Aquatic species:** Rainbow trout (*Oncorhynchus Mykiss*) **Farming period:** 60 days **Feeding days:** 52 days **Quality assessment:** Color assessment (L*, a*, b*) **Sensory analysis:** A hedonic scale using a 100 mm unstructured line scale (0 = very good quality; 100 = unacceptable) was applied. Assessors evaluated the intensity of odor, taste, aftertaste, and consistency. **Number of assessors:** 10 trained assessors **Test sample:** skinned fish fillet **Sample preparation:** Skinned fish fillets were stored on ice for 2 h, and cooked separately in glass jars for 15 min at 150°C in an electric oven. No salt, oil, or spices were added. Cooked samples each 30 g presented to the panelists. **Results:** Regarding the odor and taste, treatment I was less acceptable compared to the fillets of treatments C, S, and HS. No significant differences among fillets from treatment H and from other treatments were observed for these attributes. The presence of an aftertaste was significantly higher for treatment I compared to other treatments. The whiteness of fillets was increased significantly with the incorporation of insects in the feed formulation (treatments HS and I). Only treatment HS showed a significantly lower redness value than treatment H. There was no significant difference in yellowness between treatments. Control treatment (C) indicated significantly lower hardness compared to treatment I. Changes in meat texture and color of insect-fed rainbow trout, especially those fed with high inclusion levels of house crickets, may reduce their market acceptance.

Table 3 continued:

No.	Type of ingredient	Methods and results
3	2 different meals of partially defatted black soldier fly (BSF) (*Hermetia illucens*) larva meal Ref. Lock *et al*., 2016	**Inclusion levels**: A25%, A50%, A100%, B25% and B100% FM replacement. The control diet (fishmeal 100) represented a modem salmon diet where 50% of the oil was from a vegetable source (rapeseed) and 50% from fish oil. **Aquatic species:** Atlantic salmon **Farming period:** 105 days **Feeding days:** 51 days **Quality assessment: -** **Sensory analysis:** sensory attributes including, taste and flavor: sour, metallic, bitter, briny, fish oil, vegetable oil, rancid, cloying, aftertaste, odor: sour, metallic, briny, fish oil, vegetable oil, rancid, and texture: hardness, fatness, juiciness. The intensity of each attribute was scored from 1 to 9 (1= low intensity and 9= high intensity). **Test sample:** fish fillet **Number of assessors:** an accredited testing panel of 11 assessors **Sample preparation:** The samples initially were heated in a combi-steamer at 80 °C for 8 min. Samples were then put in a steel container placed on a heated plate (65 °C) in each assessor's booth. **Results:** The trained assessors were unable to find any significant differences among the cooked treatments for odor, flavor, or texture among the groups.
4	Partially defatted black soldier fly (BSF) (*Hermetia illucens*) Ref. Zhou *et al*., 2018	**Inclusion levels**: 3.5%, 7%, 10.5% and 14% to replace fishmeal protein **Aquatic species:** Jian carp (*Cyprinus carpio var.* Jian) **Farming period:** Not specified. The fish were acclimated in fiberglass tanks for 2 weeks before starting the experiment. **Feeding days:** 56 days **Quality assessment:** Proximate composition, amino acids profiles **Sensory analysis:** - **Results:** There were no differences in proximate composition while increasing BSF larvae meal levels led to a significant increase in saturated fatty acids, such as lauric acid, myristic acid, and palmitic acid, and a decrease in polyunsaturated fatty acids, such as linoleic acid, eicosatetraenoic acid, and docosahexaenoic acid in the whole body and muscles of the fish.
5	Black soldier fly (BSF) (*Hermetia illucens)* prepupae meal Ref. Borgogno *et al*., 2017	**Inclusion levels**: 0, 25, and 50% of BSF replacing fishmeal, respectively. **Aquatic species:** rainbow trout (*Oncorhynchus mykiss*) **Farming period:** 92 days **Feeding days:** 78 days **Quality assessment:** Proximate analysis, fatty acid composition, cooking loss, WB-shear force **Sensory analysis:** Descriptive analysis and Temporal Dominance of Sensation methods. A 9-point hedonic scale (1= extremely weak and 9= extremely strong) was also used. **Test sample:** fish fillet **Number of assessors:** Ten assessors (2 females and 8 males) aged from 20 to 30 years. Panelists attended three 60 min training sessions. A sensory lexicon list describing the sensory attributes of the samples was developed. **Sample preparation:** Frozen fillets were defrosted at 4°C for 24 h. They were washed and dried with paper, and the skin was removed. The section close to the tail was separated and the fish bones were removed. The fillets were then cut into several parts of 4±0.2 g each. Every portion was wrapped in aluminum foil, and stored at 6-8°C. Before evaluation samples were steam cooked for approximately 90 s, and immediately presented to the assessors. **Results:** Texture, followed by flavor and taste, were the first sensations to be perceived as the dominant attributes. With increasing BSF in the diet, tissue tenderness decreased. Cooked fish flavor, algae flavor, and umami taste were the dominant characteristics of the BSF I0% sample. In BSF 25% and BSF 50% samples, the metallic flavor was evident.

Table 3 continued:

No.	Type of ingredient	Methods and results
6	Partially defatted black soldier fly (BSF) (*Hermetia illucens*) Larvae meal Ref. Renna *et al.*, 2017	**Inclusion levels**: 20% and 40%- 25%, and 50% fishmeal substitution **Aquatic species:** Rainbow trout **Farming period:** 92 days **Feeding days:** 78 days **Quality assessment:** Chemical composition and fatty acid profile pH, lightness (L*), redness, (a*) and yellowness (b*), **Sensory analysis:** - **Results:** No significant differences were found in the pH and color of the fillets. Only protein content was unaffected by sample groups. The incorporation of HI larvae meals gradually increased dry matter and fat content in BSF 25% and BSF 50% compared to BSF 0%. Ash content was higher in HI0 in comparison to the BSF 25% group, while HI50 received intermediate values. 50% incorporation increased the fat content and reduced valuable PUFA contents.
7	Defatted black soldier (*Hermetia illucens*) Larvae meal Ref. Mancini *et al.*, 2018	**Inclusion levels**: 25%, and 50% fishmeal substitution **Aquatic species:** Rainbow trout (Oncorhynchus mykiss) **Farming period:** 92 days **Feeding days:** 78 days **Quality assessment:** Proximate composition, color parameters, nucleotides concentration, fatty acids profile, volatile organic compounds, and myofibrillar and sarcoplasmic concentrations **Sensory analysis:** - **Results:** Application BSF diets did not influence the proximate composition of fish meat. A diet with 50% inclusion decreased fillet yellowness. Adenosine monophosphate level was negatively affected in both inclusion diets. With the incorporation of BSF in the diet, the amount of saturated fatty acids, mainly lauric acid, increased and the amount of monounsaturated and polyunsaturated n-3 and n-6 fatty acids decreased. Fewer changes in volatile organic compounds were reported because only the concentrations of heptanal and octanal were affected, no new compounds appeared in relation to the inclusion of BSF. Even when myofibrillar content was reduced in 50% BSF fed trout, no changes in protein patterns were shown. The results showed that the chemical changes in the fillets are related to the chemical composition of BSF meal and its inclusion percentage in the diet. The inclusion of BSF in the amount of 50% in the diet reduced the yellowness of fillets and increased the content of SFA (lauric acid) and MUFA and decreased the content of PUFA.
8	Partially defatted black soldier fly (BSF) (*Hermetia illucens*) Larvae meal Ref. Secci *et al.*, 2019	**Inclusion levels**: 0, 25%, and 50% fishmeal substitution **Aquatic species:** rainbow trout (Oncorhynchus mykiss) **Farming period:** 92 days **Feeding days:** 78 days **Quality assessment:** pH, shear stress, color and water holding capacity and lipid oxidation of fillets during 120 days of frozen storage and following cooking. **Sensory analysis:** - **Results:** The incorporation of HI had no influence on the pH, shear stress, color, and water-holding capacity of the fillets (frozen/cooked). Applying 50% BSF increased the SFA and decreased the MUFA and the PUFA contents. No significant differences were found for the TBARS in raw fillets.

Table 3 continued:

No.	Type of ingredient	Methods and results
9	Defatted black soldier (*Hermetia illucens*) Larvae meal Ref. Stadtlander *et al*., 2017	**Inclusion levels**: 28.1%- 46% fishmeal substitution **Aquatic species:** Rainbow trout **Farming period:** Not specified. **Feeding days:** 49 days **Quality assessment:** Proximate composition, fatty acid profile **Sensory analysis:** Difference tests in odor, color, texture and taste, using a 9-point scale (0=does not apply and 9= applies fully). **Test sample:** Fish fillet **Number of assessors:** Fifteen untrained panelists **Sample preparation:** Fish fillets were cut into 3 pieces, wrapped in aluminium foil, and steam-cooked without pressure for 8-10 min at 100 °C. **Results:** No differences in proximate, chemical composition and sensory differences were reported. By incorporating HI, PUFA content including EPA and DHA and lauric acid amount were decreased and increased respectively. Fish fed HI had darker color compared to the control.
10	Black soldier (*Hermetia illucens*) pre-pupa normal (N) or enriched (E)) Ref. Sealey *et al*., 2011	**Inclusion levels**: 16.4 and 32.8% (N); 18.12 and 36.24% (E); 25 and 50% FM substitution **Aquatic species:** Rainbow trout **Farming period:** Not specified **Feeding days:** 56 days **Quality assessment:** Proximate analysis, amino acid, and fatty acid compositions. **Sensory analysis:** triangle difference test **Test sample:** fish fillet **Number of assessors:** A group of 30 untrained assessors (16 females and 14 males) with an average age of 41. **Sample preparation:** Frozen fillets were partially thawed and about 1 cm was removed from the head and ventral. Then about 9 g of fish meat was sliced across the fillet from dorsal to ventral. Skinless fillet portions were placed in boil-in pouches, vacuum-packed, and returned to the freezer (−23°C). Before sensory analysis vacuum-packed frozen trout fillets were defrosted at room temperature. Samples were poached for 6 min at 74 °C in a water bath, then removed from the boiling pouch and held under radiant heat for a maximum of 15 min before serving to panelists. **Results:** Using BSF prepupae in fish diet changed the moisture and lipid composition of fish meat significantly. The incorporation of BSF prepupae significantly increased muscle moisture and decreased lipid compared to the control treatment. It had no effect on amino acid content but changed the fatty acid profile significantly. Lauric acid content was increased in fish that received all BSF diets. Enriched BSF improved the EDA and DHA contents in the raw fish. No significant differences were detected among treatments.
11	Full-fat yellow mealworm (*Tenebrio molitor*) larva meal Ref. Belforti *et al*., 2015	**Inclusion levels**: 25 and 50% fishmeal substitution **Aquatic species:** Rainbow trout **Farming period:** Not specified **Feeding days:** 90 days **Quality assessment:** Proximate and fatty acid compositions **Sensory analysis:** - **Results:** TM incorporation in the diet increased protein and decreased fat contents in fish meat respectively in comparison to control. Accordingly, the control had higher EPA and the DHA contents.

Table 3 continued:

No.	Type of ingredient	Methods and results
12	Full-fat yellow mealworm (*Tenebrio molitor*) larva meal Ref. Iaconisi *et al*., 2018	**Inclusion levels**: 25 and 50% fishmeal substitution **Aquatic species:** Rainbow trout **Farming period:** Not specified **Feeding days:** 90 days **Quality assessment:** Proximate and fatty acid compositions, pH, color, water holding capacity, shear force cooking loss **Sensory analysis:** - **Results:** TM incorporation in the diet did not influence the proximate composition, pH, water holding capacity, cook loss, texture and fish meat color (raw and cooked), but decreased EPA and DHA content in fish meat.
13	Full-fat yellow mealworm (*Tenebrio molitor*) larva meal Ref. Piccolo *et al*., 2017	**Inclusion levels**: 25 and 50% fishmeal substitution **Aquatic species:** Gilthead seabream (*Sparus aurata*) **Farming period:** Not specified **Feeding days:** 163 days **Quality assessment:** marketable characteristics, color measurement (L*a*b*), **Sensory analysis:** - **Results:** Inclusion TM had no negative effect on the marketable indexes. At 50% of the mealworm inclusion level, dressed yield was decreased (raw). Fish fillets fed 50% mealworm had higher yellowness compared to the control.
14	Full-fat yellow mealworm (Tenebrio molitor) larva meal Ref. Iaconisi *et al*., 2017	**Inclusion levels**: 0, 25 and 50% of fishmeal replacement **Aquatic species:** blackspot sea bream (*Pagellus bogaraveo*) **Farming period:** Not specified **Feeding days:** 131 days **Quality assessment:** Proximate composition, pH, water holding capacity and texture characteristics, color measurements, **Sensory analysis:** - **Results:** The dietary treatment did not influence the proximate analysis and water-holding capacity and texture characteristics of fillets. But the fatty acid profile of the fillet was affected by the dietary treatment. The pH value was reported lower in fish fed 50% mealworm compared to the other treatments. EPA was higher in the control treatment. Linoleic acid significantly increased with mealworm incorporation into the diets. The yellowness and chroma were higher in fish fillets when mealworms were incorporated into the diets compared to the control.
15	Full-fat yellow mealworm (*Tenebrio molitor*) larva meal Ref. Panini *et al*., 2017	**Inclusion levels**: 0, 25, 55, 75 and 100% fishmeal substitution **Aquatic species:** farmed shrimp (*Litopenaeus vannamei*) **Farming period:** Not specified **Feeding days:** 42 days **Quality assessment:** Proximate and fatty acid composition, color and Textural analysis **Sensory analysis:** - **Results:** The dietary treatment was not changed protein, moisture, and ash contents and color and firmness of shrimp meat significantly but it increased lipid content. The absence of long-chain polyunsaturated fatty acids in MW composition resulted in a linear decrease in eicosapentaenoic and docosahexaenoic fatty acids in shrimp meat with increasing levels of mealworm in the diet.

Table 3 (continued):

No.	Type of ingredient	Methods and results
16	Defatted yellow mealworm (*Tenebrio molitor*) larva meal Ref. Basto *et al.*, 2023	**Inclusion levels**: 50 and 100% fishmeal substitution **Aquatic species:** European sea bass juveniles **Farming period:** Not specified **Feeding days:** 21 days **Quality assessment:** Proximate composition, color and Textural analysis **Sensory analysis:** consumer test **Test sample:** fish fillet **Number of assessors:** A group of 60 untrained assessors. **Sample preparation:** Fish was cut into 3 pieces each about 4 cm thick. They were wrapped in micro-perforated foil and steamed for 12 min at 100 °C in a preheated industrial oven with steam. Each untrained panellist analysed the 3 samples. **Results:** The deftated TM-based diets had the highest concentrations of n-6 PUFA, and slightly lower n-3/n-6 PUFA ratio compared to the control diet. Whole-body moisture, protein, energy, ash and phosphorus levels were not affected by dietary treatments. The whole-body total lipids significantly increased in fish fed deffated TM dietary treatments but this pattern was not observed in muscle. Hardness, adhesiveness, springiness, and chewiness parameters remained similar among dietary treatments. Cohesiveness and resilience were significantly higher in fish fed TM50 compared to those fed control. Fish skin and muscle L*, a*, b* and C* values were similar among groups. The mean rates of consumer liking were high for all fish, and the sensory panel could not perceive any significant differences in the cooked muscle samples from fish fed the different experimental diets. All samples were characterized by their soft and pleasant texture, and deffated TM samples were associated with a juicy texture.
17	Partially defatted black soldier fly (BSF) (*Hermetia illucens*) Larvae meal Ref. Cummins *et al.*, 2017	**Inclusion levels**: 0, 7, 14, 21, 26, and 36% fishmeal substitution **Aquatic species:** farmed shrimp (*Litopenaeus vannamei*) **Farming period:** Not specified **Feeding days:** 63 days **Quality assessment:** Proximate analysis **Sensory analysis:** - **Results:** Proximate analysis of farmed shrimp affected by the level of insect application. Shrimps fed with 26 and 36% BSE larvae meal had the lowest protein and fat contents.
18	Spider marine crab (SMC) meal (*P. cuvieri*), and sea urchin (SU) meal (*D. africanum*) Ref. García-Romero *et al.*, 2014	**Inclusion levels**: A control diet (CD); 2 diets replacing 10 and 20% fish meal protein with protein from SMC meal (SMC10, SMC20), and two diets with 8% and 16% inclusion of SU meal (SU8, SU16) **Aquatic species:** red porgy (*Pagrus pagrus*) **Farming period:** Not specified **Feeding days:** 180 days **Quality assessment:** Proximate and fatty acid analysis, color measurement, texture analysis, measurement of thiobarbituric acid-reactive substances (TBARS) **Sensory analysis:** - **Results:** The dietary treatment had no significant differences in fish meat proximate composition and texture. The incorporation of SMC meal could improve fish skin color and, an extension of the self-life, delay lipid oxidation during storage. Moreover, SU meal promotes yellow skin coloration in red porgy.

Table 3 (continued):

No.	Type of ingredient	Methods and results
19	Black soldier fly (*Hermetia illucens*) larvae oil Ref. Li *et al*., 2016	**Inclusion levels**: 25% (BSO25), 50% (BSO50), 75% (BSO75), and 100% (BSO100), respectively. **Aquatic species:** juvenile Jian carp (*Cyprinus carpio var. Jian*) **Farming period:** Not specified **Feeding days:** 59 days **Quality assessment:** Proximate and fatty acid analysis **Sensory analysis:** - **Results:** The addition of BSF oil did not have a significant difference in the approximate composition of fish meat among the treatments. But fatty acid compositions were affected. With the increase of BSO level, the content of lauric acid and myristic acid increased significantly in three tissues. In fish meat, the docosahexaenoic acid content of fed BSF oil was significantly higher than the control treatment. Total n-3 PUFA content slightly increased with increasing dietary BSF oil levels, while total n-6 PUFA content showed the opposite trend in muscle.
20	Fish oil (FO) and krill oil (KO) Ref. Yuan *et al*., 2020	**Inclusion levels**: 15% each in different diets **Aquatic species:** swimming crab (*Portunus trituberculatus*) **Farming period:** Not specified **Feeding days:** 56 days **Quality assessment:** Proximate analysis, and fatty acids and amino acids compositions. **Sensory analysis:** - **Results:** feeding swimming crabs with diets supplemented with marine oils, fish, and krill oil, increased the protein and indispensable amino acids contents of crab muscle. It may lead to a higher muscle content of functional amino acids such as glutamic acid, glycine, and lysine. The FO and KO diets also contributed to higher relative contents of n-3 LC-PUFA, particularly EPA, and DHA, in the crab muscle, which enhanced their nutritional value from the health of human consumers' point of view. In addition, as indicated by the analysis of volatile compounds, the muscle of swimming crab-fed diets FO and KO may have a more pleasant flavor than those fed vegetable oil diets.

In Table 4 proximate analysis of understudied insects was presented.

Banded cricket (Gryllodes sigillatus)

The banded cricket (*Gryllodes sigillatus*) has been used as a protein supplement in livestock and pets. The use of this species in aquaculture is under study. Accordingly, more feeding experiments to investigate the safe and profitable use and the effects of replacing fishmeal with this type of insect in different aquatic species were suggested (Alfiko *et al.*, 2022).

Black soldier fly (Hermetia illucens)

The first reports of sensory evaluations performed by trained and untrained assessors showed that the meat of rainbow trout (Sealey *et al.*, 2011) and Atlantic salmon (Lock *et al.*, 2016) received respectively black soldier fly (BSF) pre-pupae and larvae meals did not have significant sensory changes in fish fillet. Sealey *et al.* (2011) reported that the sensory characteristic of rainbow trout fillet was not changed when the fish received 25 and 50% normal full-fat BSF larvae meal or enriched black soldier fly larvae meal.

Similarly, sensory quality of Atlantic salmon was not varied compared to the control when fishmeal replaced completly with BSF larvae meal (Bruni *et al.*, 2020; Lock *et al.*, 2016). But, Borgogno *et al.* (2017) found significant difference in sensory attributes of rainbow trout fillet sensory when the same inclusion levels of BSF larvae meal were applied to the fish diet.

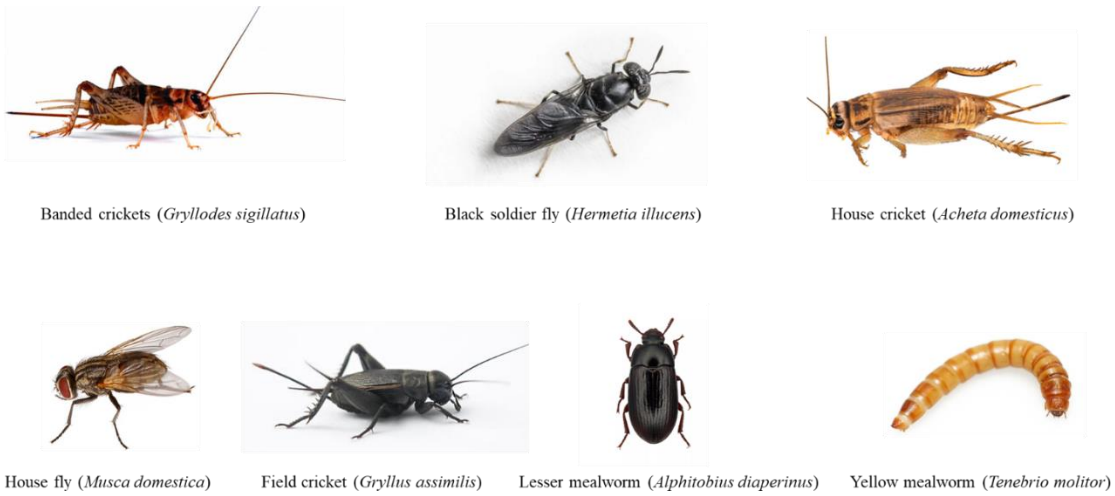

Figure 1: Seven insect species permitted by EU regulation for application in aquaculture (European Union, 2017).

Table 4: Proximate compositions (%) of seven insect species permitted by EU regulation for application in aquaculture.

Insectes	Protein	Fat	Ash	Moisture	Reference
Banded cricket (*Gryllodes sigillatus*), dried	65.66	21.51	4.84	1.95	Kępińska-Pacelik *et al.*, 2023
Black soldier fly (*Hermetia illucens*), dried	28.50	25.60	9.75	8.00	Melenchón *et al.*, 2022
House cricket (*Acheta domesticus*), dried	71.71	10.42	4.53	6.33	Udomsil *et al.*, 2019
House fly (*Musca domestica*), dried	54.02	21.72	7.63	7.54	Sanchez *et al.*, 2021
field cricket (*Gryllus assimilis*), dried	58.30	10.30	2.96	5.03	Wang *et al.*, 2004
Lesser mealworm (*Alphitobius diaperinus*), undried	20.31	9.53	1.10	66.82	Turck *et al.*, 2022
Yellow mealworm (*Tenebrio molitor*), dried	74.41	9.27	7.60	4.44	Kępińska-Pacelik *et al.*, 2023

However, Lock *et al.* (2014) reported that the method of insect meal preparation has a considerable impact on its usability. They noted that 100% fishmeal replacement by BSF meal in the diet of Atlantic salmon had no significant effect on the sensory attribute of the fish meat. Apart from the effect on fatty acid composition, other components of BSF larvae meal such as chitin may also affect the sensory quality. Because it has been reported that chitosan, a derivative of chitin, can improve the sensory quality of seafood (Fan *et al.*, 2009; Mohan *et al.*, 2012; Farajzadeh *et al.*, 2016).

The addition of BSF larval meal in the diet of Atlantic salmon (Bruni *et al.*,

2020) and European seabass (Moutinho *et al.*, 2021) did not have a significant effect on their meat color. BSF larvae have been reported to have the ability to delay lipid oxidation in Atlantic salmon (Bruni *et al.*, 2020) and European seabass (Moutinho *et al.*, 2021) fillets. The presence of chitin or antimicrobial peptides in the meal of BSF larvae may have been effective to reduce lipid oxidation. Previously, it has been reported that antimicrobial peptides in BSF larvae have defensive power against bacteria and fungi (Park *et al.*, 2014; Park *et al.*, 2015; Elhag *et al.*, 2017). Therefore, it can be concluded that BSF larvae can be used as a functional material to delay the oxidation process and thus increase the shelf life of fish.

Untrained assessors did not detect a significant difference in the meat taste, flavor, and odor of BSF-fed rainbow trout, while they had a darker fillet color than the control group (Stadtlander *et al.*, 2017). Conversely, trained panelists detected significant changes in the odor, flavor, color, and texture of rainbow trout (Borgogno *et al.*, 2017) and Atlantic salmon (Belghit *et al.*, 2019) fed BSF larval meal. In another report, a metallic flavor was noted in rainbow trout fillets fed 20–40% BSF (Borgogno *et al.*, 2017), while a strong rancid odor was observed for cooked Atlantic salmon fillets fed 100% BSF larval meal in their diet (Belghit *et al.*, 2019).

Unlike fish, the influence of dietary BSF on the quality of shellfish (especially shrimps) has received very limited attention. Maximal total body fat content was also noted in shrimp fed a 15% level of BSF larval meal inclusion in their diet (Cummins *et al.*, 2017). An increase in dry matter and fat content of trout back fillet was found by Renna *et al.* (2017) in fish that received 40% of BSF larval meal as the highest level in their diet compared to 20% of BSF and fishmeal-fed treatments. In addition, Zhou *et al.* (2018) noted no significant variation in BSF larval meal use on the proximate composition of carp. Belghit *et al.* (2018) also noted no changes in the proximate composition of BSF-fed Atlantic salmon.

It is reported that increasing levels of BSF meal in freshwater fish diet can increase saturated fatty acids (mostly lauric acid, C12:0) and decrease polyunsaturated fatty acids (both n-3 and n-6) contents in fish meat. The reason is that BSF larvae contain high levels of SFA (Mancini *et al.*, 2018; Renna *et al.*, 2018; Zhou *et al.*, 2018; Secci *et al.*, 2019). Increasing saturated fatty acids levels in the diet of this fish led to a decrease (Lock *et al.*, 2016) or an increase in the n-3/n-6 ratio and an increase in EPA and DHA contents (Belghit *et al.*, 2019).

Sensory evaluation on tilapia, rainbow trout, and channel catfish indicated no significant differences between fish that received the control diet containing fishmeal as compared with fish fed the BSF diet (Bondari and Sheppard, 1981; Sealey *et al.*, 2011). In the meat of juvenile yellow catfish (*Pelteobagrus fulvidraco*) that the feed was replaced by 20% fishmeal with BSF larvae meal for 8 weeks, no significant change of proximate analysis was seen compared to the control group.

Without affecting meat quality, defatted BSF larva meal can be used in rainbow rainbow trout diets up to a maximum of 40% (Renna *et al.*, 2017). Stadtlander *et al.* (2017) reported that replacing fishmeal with BSF larva meal (up to 50%) for 7 weeks of feeding could improve the quality of fish meat significantly. Cardinaletti *et al.* (2019), reported that the incorporation of dietary full-fat BSF larva meal did not influence the quality of the rainbow trout fillets but affected lipid metabolism negatively.

Complete replacement of fishmeal with BSF larva meal did not influence the quality of Atlantic salmon fillets, but increased neutral n-3 PUFA significantly in the fillets (Bruni *et al.*, 2020). Dietary substitution of BSF larva meal with fishmeal in the Atlantic salmon diet had not significant influence on the lipid, protein, amino acid composition, and sensory attributes of the fish fillet (Belghit *et al.*, 2019).

The influence of replacing dietary fishmeal with BSF larva meal on fillet quality in European Seabass (*Dicentrarchus labrax*) juveniles over a 62-day period indicated that replacing fishmeal with BSF larva meal up to 19.5% did not affect fillet quality or fish shelf life (Moutinho *et al.*, 2021). The total replacement of fishmeal with BSF larvae meal in the diets of Atlantic salmon did not influenec the sensory attributes of the fillet (Belghita *et al.*, 2019).

Borgogno *et al.* (2017) found significant differences in odor, flavor, and texture in the rainbow trout fillet that received dietary BSF larva meal. Increasing its incorporation in the diet increased the metallic flavor in the fish fillet. Decrease fish growth (Kroeckel *et al.*, 2012), and reduced palatability of the diet and protein digestibility (Kroeckel *et al.,* 2012) are found when high application levels of BSF larvae in fish feed (greater than 33%) was used.

Lock *et al.* (2015) reported that the use of BSF up to a level of 50% in Atlantic salmon diets did not affect fish growth or fillet quality. However, replacing fishmeal with insect meals increases the amount of fat or changes the nature of lipids in fish meat (Sealey *et al.,* 2011) and as a result, can change the flavor of fish fillets. On the other hand, it has been reported that the use of insect meal in the amount of 10 to 50% in the fish diet has no significant effect on the aroma or taste of fish and the change of fatty acid profile (Makkar *et al.,* 2014). No significant differences were found in sensory attributes of Atlantic salmon (Lock *et al.*, 2015) or rainbow trout (Sealey *et al.*, 2011) when fed up to 50% BSF meal.

Catfish and tilapia fed only complete larval BSF were less acceptable due to different flavors and textures than fish fed a commercial diet or partially fed larval BSF (25 or 50%) (Bondari and Sheppard, 1981). However, Belghit *et al.* (2019) study showed that the complete replacement of fishmeal with BSF meal had no effect on the growth performance or sensory attributes of salmon. Mancini et al. (2018) reported a reduction in yellowness of rainbow trout fillet received the highest incorporation level (40%) of BFS larval meal in their diet.

House cricket (*Acheta domesticus*)

The application of house cricket meal as a source of animal protein in aquafeed is under study (Nikoletta, 2019). Three-month feeding of perch (*Perca fluviatilis*) by replacing 25% of fishmeal with house cricket showed that fish meat fed with insect pellets had more linoleic fatty acid and n-6 fatty acids than the control group. Changes in the fatty acid composition of these fish were minimal, and their nutritional value was not affected (Khalili Tillami *et al.*, 2020).

Housefly (*Musca domestica*)

Housefly has been already used in tilapia, catfish, and other farmed fish species as a fish protein supplement. It has been reported that when 15-68% of housefly maggot feed is used to replace fishmeal in the Nile tilapia fish diet, it is necessary to add n-6 and add n-3 fatty acids (Ogunji *et al.*, 2008).

Field cricket (*Gryllus assimilis*)

Documents on the application of cricket meal (*Gryllus assimilis*) to replace fishmeal in aquafeed have just begun (Fontes *et al.*, 2019). The research on the application of this protein source in aquaculture has focused on the health and growth performance of fishmeal replacement. Most studies have shown that partial replacement of fishmeal does not have a negative effect on meat quality. However, it seems impossible to replace all fishmeal in most aquaculture species. Higher cricket meal content in farmed fish influences the sensory attributes of fishfilletst. This issue can have a negative effect on the use of crickets in aquatic feed, especially for salmonid culture. More research is needed on the effect of cricket meals on fish proximate analysis and meat quality (Fontes *et al.*, 2019). Recently, Hanan *et al.* (2021) reported that replacement of 100% fish meal with field cricket meal gave negative impact to the growth, increased lipid and decreased protein content in whole body of red hybrid tilapia.

Lesser mealworm (*Alphitobius diaperinus*)

Studies on the use of mealworms in fish farming have been reported. However, Gasco *et al.* (2016) noted that using up to 25% of mealworm as a fishmeal substitute in diets of European seabass (*Dicentrarchus labrax*), altered the fatty acid profile of the fish flesh.

Silkworms (*Bombyx mori*)

There are many reports on the use of dried silkworm pupa (SWP) in the diet of larvae or fry, mainly in cyprinids, and many other fish species. These reports indicate that the growth traits and feed performance and sensory quality of fish were not affected by the incorporation of SWP in the diet at levels below 50% even when it was not defatted (Henry *et al.*, 2015). Nandeesha *et al.* (1990) showed that if sardine oil is replaced with silkworm pupa oil in conventional carp feed, sensory characteristics are improved. A 90-day growth experiment showed that silkworm pupa can completely replace fishmeal and can comprise up to 50% of the diet of common carp (*Cyprinus carpio*). The protein content of the meat increased, while the fat content decreased with increasing pupa content in the diet. Sensory evaluation of fresh and cooked meat in 1.5% brine revealed that there were no significant differences between samples, either in overall acceptance or in sensory characteristics (Nandeesha *et al.*, 2000). Similar reports found no significant difference in sensory attributes in cyprinids received SWP oil (Jayaram *et al.*, 1980; Nandeesha *et al.*, 1999, 2000) or non-defatted SWP meal (Nandeesha *et al.*, 2000).

Yellow mealworm (*Tenebrio molitor*)

Iaconisi *et al.* (2017) found no significant differences in water holding capacity, hardness, cohessiveness, gumminess, and stickiness in blackspot seabream fed with a high-fat meal of yellow mealworm (YM) larvae to replace up to 50% of fishmeal compared to the control treatment. Iaconisi *et al.* (2018) found no significant differences in water holding capacity, cooking loss and texture of rainbow trout fed diets containing up to 50% high-fat YM larvae compared to control diets. These findings also suggest that dietary supplementation with YM may not affect consumers' preferences for fish fillets. However, more research should be done to better evaluate the effects of dietary YM in other aquaculture species.

Panini *et al.* (2017) reported that the inclusion of YM larval meal in the diet of Pacific white shrimp (*Litopenaeus vannamei*) even when using levels above 15%, which increases fat and decreases PUFA in the meat, does not have a significant effect on the final meat quality of the shrimp. No significant difference was reported in proximate meat analysis of rainbow trout fed YM compared to fish fed a fishmeal-based diet (Rema *et al.*, 2019; Jeong *et al.*, 2020). On the contrary, Belforti *et al.* (2015) reported a significant increase for protein and a significant decrease in fat in rainbow trout fillets in a fish diet with 25% and 50% YM compared to the fishmeal-fed treatment.

Feeding blackspot seabream with a YM-based diet changed the color of the skin in the abdominal area. While the skin color of the back area did not change significantly (Iaconisi *et al.*, 2017). No significant effect was observed on the fillet color of rainbowtrout-fed YM-based meals. However, dorsal skin color had a higher redness index in the group that received fishmeal than in the group fed a diet with 25% fishmeal replaced with high-fat YM larvae (Iaconisi *et al.*, 2018). The presence of riboflavin as a yellow pigment in insects has been reported (Finke, 2002). Accordingly, the increased yellowness of the flesh of blackspot sea bream (*Pagellus bogaraveo*) fed YM-based diets has been attributed to the presence of riboflavin as a yellow pigment in insects (Iaconisi *et al.*, 2017).

In addition, the highest contents of protein and fat in rainbow trout fillets received diets incorporated with up to

60% YM reported by Hersij *et al.* (2019). No significant differences were reported in the proximate analysis of European seabass (*D. labrax*) received diets containing 25% and 50% YM larvae. While reduction of DHA and EPA fatty acids in fish received diets contained 50% YM larvae has been reported (Gasco *et al.,* 2016). An increase in the linoleic acid content in the muscles of European sea bass (*Dicentrarchus labrax*) received diets incorporated with defatted YM larvae at the level of 80% of dietary fishmeal was reported (Basto *et al.,* 2021). This level of inclusion had no significant effect on the contents of EPA and DHA.

Reyes *et al.* (2020) reported that no significant variations in the proximate composition of European sea bass (*Dicentrarchus labrax*) fillets received diets with 50% of fishmeal replaced with YM larvae were observed. On the contrary, Mastoraki *et al.* (2020) found a significant reduction in protein, dry matter and fat, as well as the highest content of PUFA in European sea bass (*Dicentrarchus labrax*) revieved diets with 30% of fishmeal replaced with whole YM larvae.

Piccolo *et al.* (2014) showed no significant changes in proximate body analysis in gilthead seabream reciev diets with 25% and 50% fishmeal substituted with YM larvae. Iaconisi *et al.* (2017) noted the same results in blackspot seabream recieevd diets with 25% and 50% fishmeal substituted with full-fat YM larvae. They also reportd a significant increase in linoleic acid with increasing levels of full-fat YM larval diets. Higher alanine, arginine, glycine, leucine, lysine, and proline and lower histidine, taurine, and phenylalanine levels in gilthead seabream received diets with 50% replaced with full-fat YM larvae were reported by Iaconisi *et al.* (2019). They showed that the profile of amino acids in salmonid fillets fed diets with YM-replaced fishmeal depends on the replacement percentage and may require fine-tuning of the feed formulation, especially amino acids, to prevent deficiencies.

Iaconisi *et al.* (2018) revealed an increase in palmitic acid, oleic acid, and linoleic acid levels, and a decrease in EPA and DHA content in salmon fillets with increasing levels of YM inclusion up to 50% of diets. Sanchez-Moros *et al.* (2016) reported no significant difference in the proximate analysis of Nile tilapia that recieved YM-based diets to replace up to 50% of fishmeal compared to the control group. Sankian *et al.* (2018) noted no differences in a proximate analysis of mandarin fish fed a diet with up to 30% full-fat YM larvae. However, higher monounsaturated fatty acids (MUFA) and lower PUFA were found in the YM-incorporated groups compared to the control group. Khosravi *et al.* (2018) reported no effect of dietary supplements with a maximum of 32% YM on proximate analysis, fillet quality, and essential amino acid composition of rockfish (*Sebastes schlegeli*).

Ng *et al.* (2001) reported the highest protein content in the meat of African catfish that received diets with fishmeal substituted with 20% YM meal. However, a higher fat content was found in the meat of catfish that received only live YM. Khoo *et al.* (2020) found no difference in mirror carp meat obtained with a diet containing 25% YM oil compared to diets containing BSF larvae oil.

No significant differences in protein and ash levels in shrimp meat that received YM-based diet with up to 100% fishmeal replacement and observed an increase in body fat content of shrimp with increasing YM levels in the diet has been reported. They noted a linear reduction in the content of EPA and DHA in shrimp meat with higher YM inclusion levels in the diet (Panini *et al.,* 2017). The use of graded YM protein levels in shrimp (*M. rosenbergii*) diets showed conflicting results, while a linear increase in fat content with decreasing protein in shrimp meat was observed with increasing YM protein inclusion in the diet (Feng *et al.*, 2019).

Dietary inclusion levels of up to 50% YM larval meal resulted in no changes in moisture, protein, or ash in shrimp muscle (Panini *et al.,* 2017) and rainbow trout (*Oncorhynchus mykiss*) fillets (raw and cooked) (Iaconisi *et al.*, 2018). It is reported that water holding capacity and texture characteristics of fillets obtained from blackspot seabream (Iaconisi *et al.*, 2017), gilthead seabream (Piccolo *et al.*, 2017), and rainbow trout (Iaconisi *et al.,* 2018) received YM larva meal were not affected by the diet. Gasco *et al.* (2018) revealed that YM larvae contain high levels of oleic, linoleic, and palmitic acid.

The aquatic origin (AO) feed

Fisheries and aquaculture by-products contain the remains of raw fish and shellfish materials that are created after processing (filleting, canning, and packaging). These compounds are highly nutritious and are commonly used to produce fishmeal and oil, fish protein hydrolyzate (FPH), and silage for animal feed. But these by-products are not fully used and this leads to economic and environmental problems at their disposal.

The approximate analysis and nutritional value of fishery by-products are significant and depend on different aquatic species (Etemadian *et al.,* 2021). Fishmeal and oil, FPH, fish silage, and algae are AOF products used in aquaculture. Replacing fishmeal in aquafeed with inexpensive protein sources, such as regionally or locally available unexploited by-products, may be an excellent opportunity for sustainable resource use (Bae *et al.,* 2019). Several works report the quality and quality changes of fish/ shellfish fed AOF. Fish oil and krill oil in the diet helped to produce more pleasant flavors by increasing the relative levels of 3-methylbutanal, heptanal, benzaldehyde, and nonanal in crab muscle, and diets containing marine oil increase polyunsaturated fatty acids in the muscle (Yuan *et al.,* 2020).

Enzyme or acid hydrolyzed by-products are now widely used to modify or improve the protein quality and digestibility of farmed aquatic animals. Hydrolyzed fish byproducts from Alaskan fisheries have been evaluated for replacement of fishmeal menhaden in white leg shrimp (*Litopenaeus vannamei*) diets (Forster *et al.,* 2011). Güllü *et al.* (2014) reported that fish silage made from fish processing by-products is a good source of protein to replace fishmeal up to 20% in rainbow trout (*Oncorhynchus mykiss*) diets without significant influence on the fatty acid composition of fish fillet. The application of tilapia silage in shrimp (*Litopenaeus vannamei*) culture showed that shrimp quality index and shelf life were not affected by silage-based diets (Gonçalves *et al.,* 2019). There was no significant difference in proximate composition between groups of cobia (*Rachycentron canadum*) fillets after a 3-month feeding experiment according to diets with or without the addition of fish silage, and no significant differences were observed in the shelf life study between the two groups reported by Mach and Nortvedt (2013).

To evaluate the influence replacing of fishmeal with fermented fish silage on Nile tilapia, (*Oreochromis niloticus*) fry a 12-week feeding experiment was carried out. The results indicated that protein and fat contents in the fish body were significantly increased and decreased respectively with increasing substituting of fishmeal by fermented silage. But ash and dry matter did not significantly change. Significant defenses were found for attributes between control and fish fed with fermented silage. The control received the highest sensory scores *i.e.* color, odor, texture, and acceptance (Soltan *et al.,* 2017).

The application of dietary shrimp shell meal (12-24%) in large yellow croaker (*Larimichthys croceus*) for a 9-week feeding trial indicated that the skin color and carotenoid content were significantly improved with the supplementation of shrimp shell meal in the diet. The TBARS was not significantly affected by dietary shrimp shell meals. High dietary shrimp shell meal (24%) decreased the growth performance and meat fat content. No significant differences in the meat protein and moisture were found. The ash content of meat significantly increased with the increase of the dietary shrimp shell meal (Yi *et al.*, 2015).

The use of crab meal as feed additives increased meat color and sensory properties in red porgy (*Pagrus pagrus*) (Garcıa-Romero *et al.,* 2014b). The use of new materials made from the processing of fish by-products can affect the quality of fish produced for human consumption due to the ease of oxidation or strong odor and, as a result, possible changes in market value, based on sensory properties and nutritional value (Iriondo-DeHond *et al.,* 2019).

The application of shrimp shell meal in hybrid tilapia (*Oreochromis niloticus x Oreochromis aureus*) farming was studied (Fall *et al.,* 2012). Application of shrimp shell meal as a replacement for fish meal at 0– 100% levels indicated that the proximate composition of the feeds did not change statistically, except for ash content. Hardy *et al.* (1984) reported that co-dried fish silage replacing 100% fishmeal in the diet did not significantly affect the sensory characteristics of feeding rainbow trout for 32 weeks. Supplemental feeding of spirulina or its extract has benefits for aquaculture. Some of these effects include increasing growth rate, increasing color, and overall texture quality (Belay *et al.*, 1996). The effect of 2% spirulina application on sarcoplasmic, myofibrillar, alkali-soluble, and stromal protein fractions in marine redfish was studied by Mustafa *et al.* (1994). Accordingly, stromal protein in fish that received spirulina incorporated diet was significantly higher than in the control diet. It is reported that stromal protein, consisting mainly of collagen, affects the texture of raw and cooked fish (Feinstein and Buck, 1984; Sato *et al.*, 1986).

Liao *et al.* (1990) revealed that Spirulina incorporated feed improved the color, texture, and taste of the ventral muscle of striped jack. The results of the use of spirulina (*Spirulina platensis*) in feeding hybrid red tilapia showed that up to 20% of spirulina can be substituted in a fishmeal-based diet for this fish without any negative effect on the proximate analysis of fish meat (Ungsethaphand *et al.*, 2010).

In a trial carried out by Nandeesha *et al.* (1998) on feeding common carp, (*Cyprinus carpio L.*) with Spirulina platensis no significant difference in carcass moisture and protein content was found. Accordingly, ash and fat contents of the carcass were positively and negatively correlated with dietary Spirulina level, respectively. No effect of Spirulina feeding on the sensory evaluation of both raw and cooked fish were reported.

Concluding remarks and future perspectives

The aquaculture industry is mainly dependent on the production of aquafeed to meet the nutritional needs of aquatic animals. In this sense, the search for non-traditional alternatives to fishmeal and fish oil is one of the main challenges needed to sustain aquaculture activities. The aquaculture industry should work to promote transparency for consumers in its production techniques and provide facts to consumers who wish to learn more about aquaculture products. Additional challenges include making an agreement on the qualitative and sensory characteristics of aquaculture products, such as color, taste, odor, lipid content and especially omega-3 fatty acid content in edible tissues. Consumers also want to be assured that aquaculture products are safe and nutritious.

Controlling the details of farmed fish production not only provides opportunities to enhance the sensory characteristics of the fish to suit the consumer's acceptance but also controls the nutritional content of a fish characteristic that is highly valuable for human health, *i.e.* omega-3 fatty acids. Using science-based nutritional methods, cultured fish can be produced to consistently meet target quality characteristics. Changing feed nutrient content can improve product quality in terms of sensory attributes, specific nutrient content, and shelf life. Aquaculture quality can be largely controlled by feeding levels, nutrient levels in the feed, ingredient selection, and the protein/lipid ratio of the feed fed in the final stages of production. IB and AO products have great potential for feeding aquatic animals in terms of overcoming the shortage of animal feed and providing animal proteins. They are good sources of nutrients for feeding aquatic animals, which can replace fishmeal or fish oil.

But the use of such substances in the feeding of farmed aquatic animals has a negative or positive effect on the sensory properties of meat. Researchers have used different proportions of these materials in the feed of the studied cultured fish, and other components of the diet were not the same in all studies. Therefore, the results of similar studies are not comparable. But the levels of use of these compounds and the perceived sensory characteristics can be used as guidelines for other researchers and industries in determining the optimal level of inclusion of such products and their sustainable use. The information related to the metabolism of these products in the body of aquatic animals is responsible for their effect on the sensory quality of meat and is an interesting topic for further research in this field. In addition, the presented sensory data can be used in the commercial application of IB and AO ingredients in the aquaculture industry.

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