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REVIEW

A review on the prospects and potentials of fishmeal replacement with different animal protein sources

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Abstract Aquaculture has adopted numerous alternatives, including plant-based sources, microbial biomass, and animal by-products, to recognize the importance of reducing fishmeal (FM) use for economic and environmental sustainability. Several studies have been conducted to look into the impact of different animal protein sources, such as meat and bone meal (MBM), feather meal (FeM), blood meal (BM), poultry by-product meal (PBM), and insect meal (IM), as substitutes for FM in the diets of various fish species. Numerous studies have revealed different degrees of favorable results and outcomes. Studies of different fish species with various levels of substitution were reviewed. Moreover, many studies have demonstrated that the development of fish is not significantly impacted by the inclusion of animal meals in their diets at low to moderate levels. Although the use of alternatives such as fishery by-products, insects and terrestrial by-products has some constraints. However, the utilization of animal-based protein sources generally exhibits positive results with regard to numerous factors, including the variable growth rate, feed conversion ratio, survival rate, and final weight of different fish species. Indeed, certain animal diets also enhanced the blood composition and immune response of certain species. Overall, the perception is that IM is the most advantageous and proactive protein source used in aquaculture. Several studies have shown that PBM and MBM reveal improved results. More research is required to further interpret other factors that influence the dietary incorporation of animal protein sources in aquaculture feeds.

Keywords Aquaculture . Fishmeal . Animal protein sources . Poultry by-product meal . Feather meal . Meat and bone meal

Introduction

The global population is increasing, with an associated increased need for food, including animal proteins (Fawole et al. 2016), which will directly affect the livestock sector. The scarcity of animal protein is an issue globally. The population's living standards are progressively improving, leading to an increased demand

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for seafood. Aquatic animals serve as a crucial and valuable source of protein for humans, making aquaculture a necessary requirement in the present day. Aquaculture is the only approach by which the increasing demand for seafood can be met. Aquaculture is the process of rearing, growing or producing aquatic organisms. With capture fisheries declining in many parts of the world, aquaculture's role is increasing in providing fish and other aquatic resources for food. The main problem that aquaculture is facing nowadays is continuous increase in the need to meet the demand of fish consumption for humans. Capture fisheries for wild fish have reached their maximum limit since the 1980s (FAO 2022). Many factors like fish species, nutrition, environmental conditions and economy contribute to the success of aquaculture (Schnaittacher et al. 2005). Aquafeeds have depended on fishmeal (FM), as a good protein source to promote good health and fast growth of farmed fish. FM is now considered unsustainable and expensive and the development of aquaculture is restricted due to high costs of aquafeeds which include FM. There is a rapid decline in source of FM because it depends on "by-catch" and harvest of forage fish, both of which deplete wild stocks. Particularly, carnivorous species raised in aquaculture need great amounts of FM so feed cost is especially high for them (Manzano et al. 2012). The scarcity and high costs of FM have caused the exploration of alternative sources with high proteins and similar nutritional benefits (Daniel 2018).

A vast variety of plant-based and animal-based protein sources have been assessed and all of them have different potentials and varying success as alternatives to FM in aquafeeds (Poolsawat et al. 2021). Because of the need for alternative sources of feed to contain similar magnitude of nutritional products as conventional feeds, some alternatives are less favorable because they have high fiber content, unbalanced fatty acids, amino acids (AAs) content (methionine, lysine) and anti-nutritional factors that would not make them sufficient (Daniel 2018). It has been proposed that alternative protein sources should be available in market which has better or at least similar AAs profile to FM-based diets and have comparable palatability (Sing et al. 2014). A combination of different protein sources is presumed to be better than a single source of protein because the mixture has a preferable AAs profile which results in better growth performance.

Plant-based sources are being used in aquaculture but large amounts of plant-based feeds are not encouraged because they contain anti-nutritional components. They also have non-starch polysaccharides with AAs and fatty acid profiles which are less preferable (Daniel 2018). Many animal protein sources also are used as substitutes for FM (e.g., feather meal (FeM), PBM and Antarctic krill meal). Millamena (2002) outlined that the substitution of 80% of FM with animal protein sources (i.e. blood or meat meal) could produce better or similar growth rates in several different fishes. It is confirmed by many studies that diets including 30-70% meat meal used as an alternative to FM are readily acceptable by many carnivorous and omnivorous fishes (Millamena 2002; Ai et al. 2006). The substitution of FM with various plants and terrestrial animal sources has been causing reduction in the cost of FM in many countries.

Nevertheless, the demand for protein sources as substitutes or alternatives to FM probably needs to double (Woodgate et al. 2022). Animal protein sources seem to be better solutions than plant protein sources because they have higher amounts of protein and lipid, essential AAs and better digestibility (Table 1). So far, it appears that completely eliminating FM from aquafeeds has a negative impact on the health of fish (Macusi et al. 2023). But many authors have reported that between 30% and 70% of FM could be replaced by rendered animal by-products (Ai et al. 2006). Rendering is an industry that has existed since the people started to use animal products in meals. In rendering, animal by-products are processed from land-farmed animals (Woodgate et al. 2022; Fig. 1).

Replacement of FM with poultry by-product meal (PBM)

PBM is obtained from ground, rendered, or clean parts of the carcass of slaughtered poultry. Different rates of success have been observed by using different levels of PBM in various aquaculture species (Glencross 2016; Yu et al. 2023). PBM is an easily accessible and cost-effective ingredient. In relation to FM, it contains a significant amount of protein and the majority of essential AAs, except lysine and methionine. Similar to other forms of animal-based protein, the digestibility of PBM might vary due to differences in its quality and content. This variability poses a challenge when using PBM. Several studies have been conducted in order to investigate the effects of PBM, but the results of these investigations have been inconsistent. Glencross (2016) described that the introduction of PBM up to the range of 338 g/kg has no negative impact on the growth but it could have harmful effects beyond this level.

Chaklader et al. (2021) illustrated the effect of replacement of FM with different levels of inclusions of PBM which was supplemented with *Hermetia illucens* (HI) larvae and Tuna hydrolysate (TH). All fish fed with PBM with supplementation of HI and TH larvae showed an increase in total protein ratio, serum total bilirubin and immune response. Another study showed that PBM, meat and bone meal (MBM) and shrimp meal can be used as complete substitute for FM but BM produced less significant results in Nile Tilapia (*Oreochromis niloticus*). When PBM was supplemented with corn and sorghum, it resulted in better fish performance and therefore can be used as a replacement for FM. However, it causes higher waste loads in

Table 1 Results of different studies on substitution of fishmeal with different animal by-products

Fish specie	Animal meal	Effect	Best replacement %	References
Oreochromis niloticus	BM	Arginine, alanine and phenylalanine, increased. Leucine, lysine, isoleucine, valine and methionine, decreased.	50% replacement of FM with BM	(Kirimi et al. 2017)
Mylopharyngodon piceus	BM	Growth rate was reduced with increasing rate of inclusion of dietary BM content Activity of intestinal trypsin decreased with increasing BM content	Diet with 40% BM without having any negative effect on growth and innate immune response	(Twahirwa et al. 2021)
Arapaima gigas	Spray-Dried BM	Growth rate, feed intake and body weight increased with 0-6% BM. Food conversion ratio and protein retention decreased after 6% BM diets.	Diets with 0-6%	(Ribeiro et al. 2011)
Dicentrarchus labrax	Black soldier fly pre-pupae meal (HM)	No difference in growth performance. No difference in plasma metabolic profiles. Decrease in lipase activity No effect on protease and amylase activity	19.5% HM successfully partially replaced the FM	(Magalhães et al. 2017)
O. niloticus	Black Soldier Fly Larvae meal	Doesn't significantly improve growth indexes, survival No effect on RBCs, WBCs and platelets distribution Increase skin and peroxidase activities	100% replacement could be used	(Tippayadara et al. 2021)
Lemon fin barb hybrid fingerlings	Defatted black soldier fly pre-pupae meal (HM)	Enhances the growth activity up to diets of 75% replacement No pathological change	25% replacement	(Kamarudin et al. 2021)
C. gariepinus	Adult variegated grasshopper (*Z. variegatus*) meal (VGM)	Protein and lipid digestibility decreased with increase in VGM	Feed with 25% VGM	(Alegbeleye et al. 2012)
Rainbow trout	PBM and IM (*H. illucens)*	Restored α-diversity affected by VM. Diets Gammaprobacteria was reduced in HI diets	H10P50	(Gaudioso et al. 2021)
GIFT tilapia	Poultry by-products and bioprocessed poultry by-products	No difference in effect on survival rate, AAs and chemical composition of whole body and hemato-biochemical response No negative effect	66.67 %	(Sathishkumar et al. 2021)
Lates calcarifer juveniles	PBM supplemented with tuna hydrolysate and IM	80, 85 or 90% PBM with 5-10% HI Improvement in serum total bilirubin, Increase in fatty acid retention Increase in immune response No negative effect on texture	Diets with 80 and 85% PBM	(Chaklader et al. 2021)
D. labrax	FeM	Energy and protein apparent digestibility coefficients (ADC) were reduced, no change in growth, feed intake and muscle fatty acid composition.	12.5% FeM	(Campos et al. 2017)
O. niloticus	Enzymatic FeM	No significant effects on growth, nutrient retention and digestibility	Enzymatic FeM	(Poolsawat et al. 2021)
Sparus aurata	MBM	Growth performance, feed utilization, and nutrient retention improved	50% MBM	(Moutinho et al. 2017)

Abbreviations: BM = blood meal, HM = hermetia meal, IM = insect meal, PBM = poultry by-product meal, FeM = feather meal, MBM = meat and bone meal, FM = fishmeal, VM = vegetable protein meal, VGM = variegated grasshopper meal the system. PBM supplied with enzymes also increases nutrient digestibility of fish (Soltan 2009). A study by El-Husseiny et al. (2018) explained the use of PBM with supplementation of L-lysine. It suggested that partial replacement of FM is possible at the level of 50% and 75% with the addition of 1% L-lysine. Growth performance and feed utilization decreased when PBM levels increased from 50-75% or when supplied without the addition of L-lysine.

Feather meal (FeM) as a replacement for fishmeal

FeM, although widely available as a by-product of poultry harvests, has not been considered a strong candidate for aquafeeds due to lack of essential AAs and indigestibility of protein (Li et al. 2009). Nevertheless, FeM is a cheap and widely available meal (Poppi et al. 2011). It has high protein content (800-900 g/kg crude protein), and a great amount of AAs such as threonine, arginine and cystine (Tesfaye et al. 2017). Lysine, methionine, tryptophan and histidine are some essential AAs that are in less quantity (Klemesrud et al. 2000). The consumption of chicken is increasing nowadays so the poultry industry is flourishing and rising in contribution of feather waste. 6-9% body weight of the chicken is its feathers and they have almost 91% protein, 1% lipid and 8% water (Schrooyen et al. 1999). There is a processed animal protein source known as hydrolyzed FeM which contains about 80% crude protein (Poolsawat et al. 2021) but the major protein in it is keratin which cannot be digested. Nevertheless, it was approved in 2013 for use in aquafeeds. If FM was replaced with FeM at a large scale, it could be beneficial to decrease the dependence on FM and reduces the cost of aquafeeds. It has been studied in diets of European seabass (Campos et al. 2017). FeM cannot be easily digested because there is great difficulty in degrading feathers, so its decomposition takes a long time (Okareh et al. 2015; Mustapha and Adeniyi 2022). In a study by Arunlertaree and Rakyuttithamkul (2006), FeM fermented with yeast was used as a substitute for FM in Hybrid Clarias Catfish to evaluate its success. Diet with 25% inclusion showed better growth without having negative effects and the costs of diets could be reduced by about 0.81 baht/kg when 25% of FM is replaced by fermented FeM.

Blood meal (BM) as a replacement for fishmeal

BM is dehydrated waste blood after slaughter. It has almost 80% protein content, hence it can be used as an alternative to FM in terms of AA composition and crude protein content (Kirimi et al. 2017; Fig. 2). Some

Fig. 1 Rendering process of animal by-products

AAs are currently lost in the dehydrating process, which reduces the efficiency ratio.

Various studies have documented that the complete substitution of FM with BM has no significant negative influence on the growth, survival rate or feed conversion ratio (FCR) of several animals (Agbebi et al. 2009). Lysine (8.7%) and histidine (6.2%) levels are rich in BM. One study found that adding BM at a rate of 5–10% may produce the best outcomes (Karaket et al. 2022). Widespread usage of BM in aquaculture is due to its consistent quality and high digestibility (Hodar et al. 2020). Moreover, BM can also be used to prevent cataracts in cultured salmon (Sissener. et al. 2021). Kirimi et al. (2017) studied the impact of substitution of FM with BM. It has been noticed that swapping FM with BM decreased the number of essential AAs like lysine, leucine, and methionine and increased the amount of alanine, phenyl-analine and arginine in the diets. According to the results, 50% BM replacement of FM gave a good diet but complete replacement did not show a good result.

Meat and bone meal (MBM) as substitute for fishmeal

MBM is a widely-available animal by-product from slaughter houses. Many studies all over the globe are working on replacement of FM with alternative sources. One of the potential alternative sources of FM is MBM because it has high protein (45-65% crude protein) and a good ratio of AAs (Tan et al. 2005; Suloma et al. 2013; Fig. 3). There is low carbohydrate content and satisfactory AAs profile but at the same time, MBM has some limitations such as methionine and lysine insufficiency, high ash proportion and reduced digestibility. Bone is present which increases the ash content, and is the reason for less usage. The freshness of meal, processing technologies and quality of raw materials greatly affect the nutritive value of MBM (Kureshy 2000). These attributes rendered the results inconsistent. It has been used in numerous research to assess the percentage of replacement, and the findings frequently showed that it may replace FM without any adverse consequences. The replacement amount varies between 25% and 45% across different studies, and this variance can be attributed to factors such as quality, processing, and variations in fish species, size, and diet composition. There was a 30% replacement of FM with MBM in Cuneate drum (Wang 2006). In African catfish (*Clarias gariepinus*), there was 75% replacement (Goda et al. 2007). One study found a harmful correlation between growth rate and MBM replacement in red drum (*Sciaenops ocelatus*) (Kureshy 2000).

Ai et al. (2006) substituted FM with MBM in large yellow croaker (*P. crocea*). Fish fed the diet with 0, 15, 30 and 45% MBM showed no significant difference in specific growth rate (SGR) but fish fed with diets

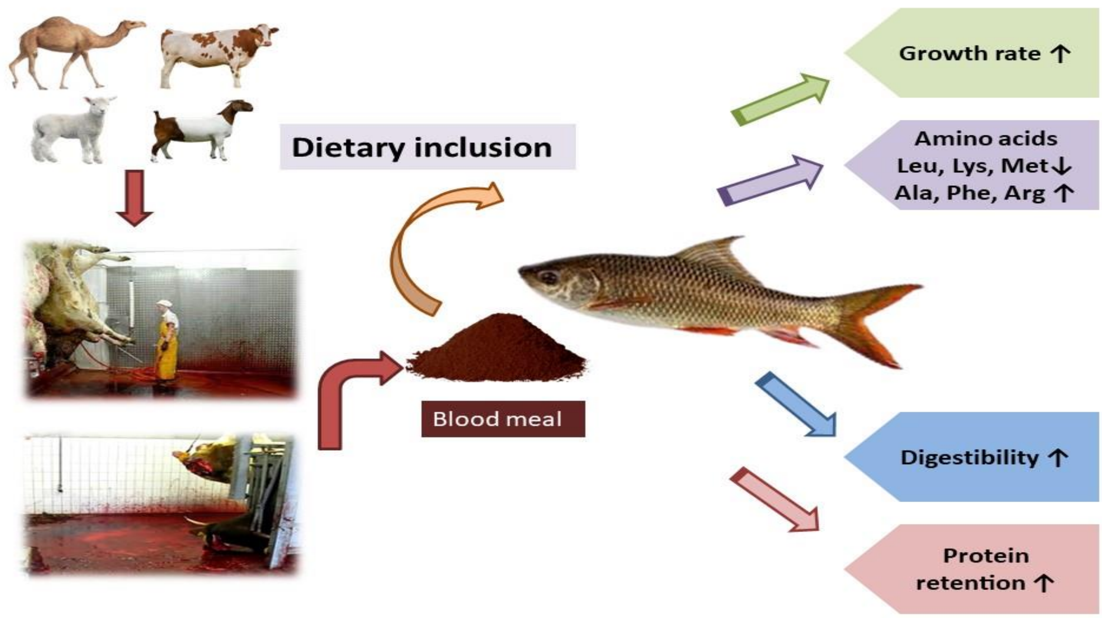

Fig. 2 Replacement of fishmeal with blood meal

60 and 75% MBM showed lower growth performance. There was no negative effect of MBM on essential AAs but increasing MBM decreased the amount of n-3 unsaturated fatty acids and lipids. The conclusion was that increasing the amount of MBM reduced the SGR because there was low digestibility.

Bharadwaj et al. (2002) found that MBM did not significantly affect the weight gain and feed conversion ratio. But inclusion of more than 30% MBM in diets negatively affected the crude protein, phosphorus and AAs ratio. So there were low nutritional values in fishes fed with diets more than 30% MBM. Moutinho et al. (2017) replaced FM with MBM in gilthead seabream juveniles. Diets with MBM0 and MBM50 didn't affect the growth rate and feed efficiency but the retention of energy was lower in fish fed with diet MBM75. In economic terms, the cost of production of MBM feeds was low. Overall it was concluded that MBM50 gave the best result.

Insect meal (IM) as a substitute for fishmeal

Recently, different IMs have emerged as promising alternatives for protein in aquafeeds because they contain similar nutritional components to FM (such as a balanced profile of essential AA) (Henry et al. 2015; Fig. 4). Also, they have less harmful impact on environment, have the added benefit of organic waste disposal, and transmit less zoonotic diseases (Van Huis 2013). Insects can be treated as attractive replacement because they have high FCR, fast growth and they could feed on bio-waste. These factors make its production highly defensible and economical.

There are factors like taxonomic group, technological process, rearing substances and high protein content (60-80%) that affect the nutrient composition of IM (Sánchez-Muros et al. 2014). There is balanced profile of essential AAs in IM (Henry et al. 2015). Rearing conditions and technological treatments can influence the insect fatty acid composition and lipid content (Barroso et al. 2014). Furthermore, problems related to fatty acid profile could be avoided by the use of defatted IM. Insects contain an adequate amount of minerals such as iron, potassium, selenium, calcium, and many important vitamins. Rearing conditions could affect the level

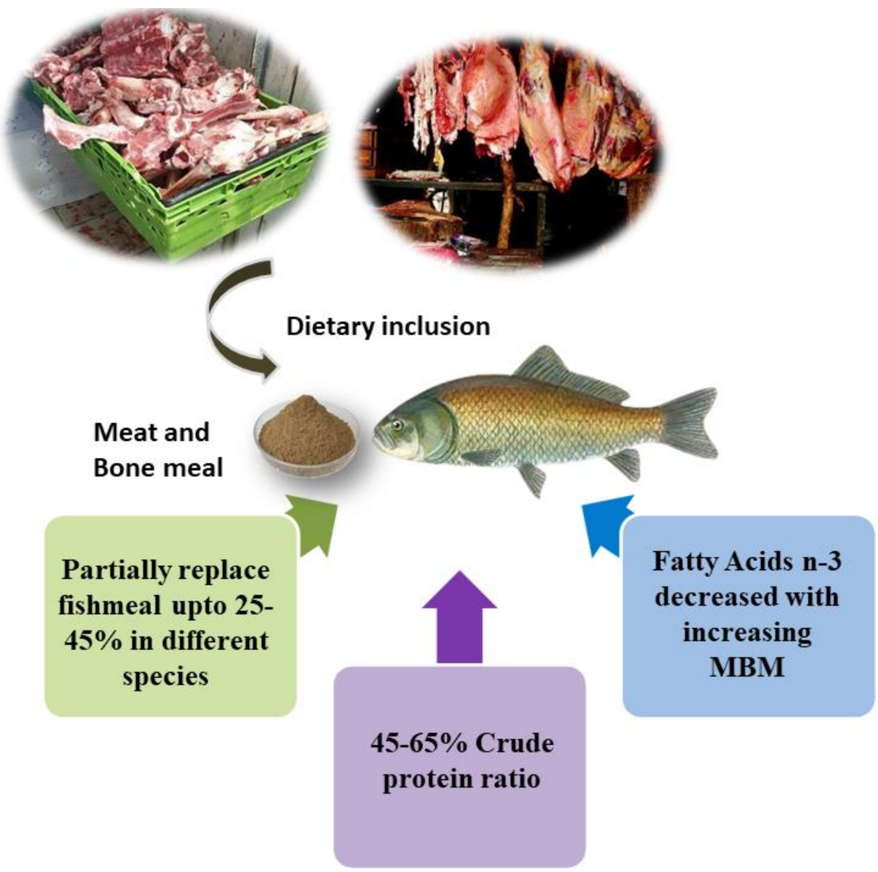

Fig. 3 Substitution of fishmeal with meat and bone meal

of these minerals and vitamins depending on the rearing conditions (Henry et al. 2015).

Mostly crustaceans and wild fish eat marine insects as a source of protein and a part of their natural diets. IMs from black soldier flies, mealworms and cricket meals are common sources.

Lipid content ranges from 8%-35% depending upon the lipid extraction method, the high protein ranges from 45-70% and there is a well-balanced essential AAs profile in insect-derived products. The nutritional value of IM is due to the amount of protein in different insect species (Rumpold and Schluter 2013). Their sub-stages are rich in proteins and lipids. It has been observed that if we replace FM more than 30% with IM, it causes decrease in fish growth (Yue and Shen 2021). Insects grow and reproduce easily, have very better growth ratio and need less space and energy as compared to other animals (Van Huis 2013). It doesn't have anti-nutritional factors and has weighed a number of AAs but the high content of fat is its major disadvantage (Kamarudin et al. 2021). Recently, black soldier flies have been mostly used because they have high rate of fertility, short rearing period and better composition of fatty acid (Smetana et al. 2019). Drying techniques like roasting, sun-drying and frying in addition to modern methods like oven-drying, freeze-drying and microwave-assisted drying are the most commonly used methods in processing of insect biomass.The substitution of FM with defatted black soldier fly pre-pupae in the feed of lemon fin barb hybrid fingerlings was studied by Kamarudin et al. (2021). Barb hybrid (*Hypsibarbus wetmorei*) fingerlings experienced enhanced SGR and weight gain with upto 75% BSFP, but growth retarded with 100% BSFP, possibly due to a high amount of chitin. These authors concluded that 25% FM is still essential for proper or optimal growth. Mapanao et al. (2021) also found that 75% BSF larvae replacement showed the best result (i.e. highest SGR and weight gain) for climbing perch (*Anabas testudineus*).

Magalhães et al. (2017) conducted a feeding trial to determine the effect of replacement of FM with Black soldier fly pre-pupae meal at rates of 15%, 30% and 45% of FM was replaced with IM. There was no effect on the plasma metabolic profile, protease and amylase activities, but a decrease in lipase activity. There was no effect on protease and amylase activity. The diet with 19.5% Hermetia meal (HM) successfully replaced the FM. Alegbeleye et al. (2012) replaced FM with adult variegated grasshopper meal (VGM) to assess its nutritive value. 6.87% crude lipid, 61.50% crude protein and 9.35% chitin were found in VGM. The best results were shown by fish fed with diet including 25% VGM.

However, the processing of IM increases its price, which prevents the aquafeed industry from utilizing IM. Therefore, combining IM with other FM substitutes could be a sensible choice in terms of price, environmental sustainability, and fish health (Gaudioso et al. 2021). Similarly, some species of insects have low calcium or phosphorus levels, which require an enhancement of minerals. Hence, proper nutritional

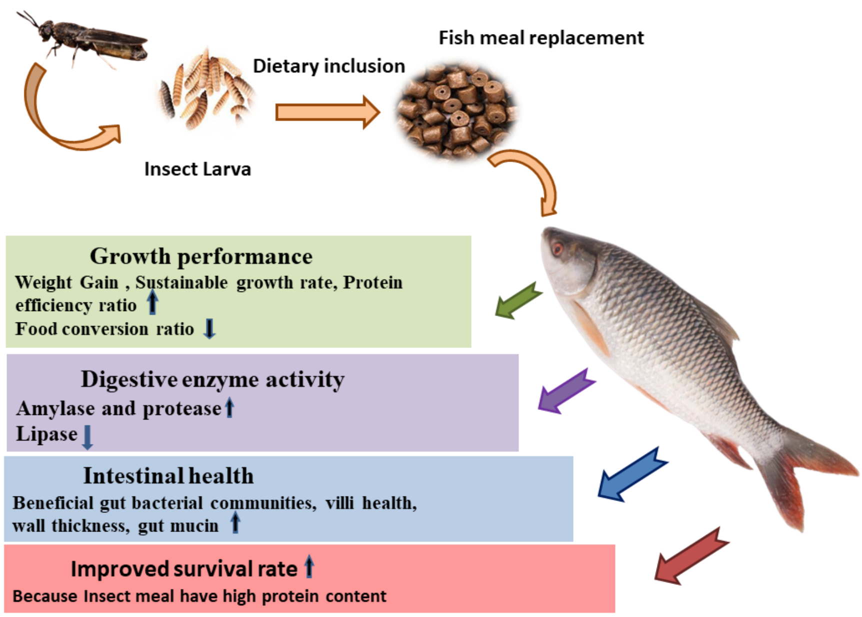

Fig. 4 Replacement of fishmeal with insect meal

assistance for insects can enhance this quality (Pinotti et al. 2019).

Conclusion

The primary factor contributing to the production costs of aquaculture systems is the expenditure on feed. Aquaculture is an industry that is highly diverse in terms of the species that are cultivated and the production systems that are used. As a result, there is a wide range of species and levels of inclusion that are adopted. The primary challenge confronting aquaculture is the unsustainable production and rising cost of FM and fish oil, which are the most reliable sources of premium proteins and lipids, respectively. Numerous protein sources can be used as substitutes for FM. These alternatives are not only more affordable but also offer a higher nutritional value in comparison. The alternative sources encompass plant-based protein sources, animal-derived protein sources, and probiotics. This review has highlighted the effectiveness of several animal protein sources, including MBM, FeM, BM, PBM, and IM, as FM alternatives in the diets of various fish species. Alternative feed selection is influenced by several factors, including fish safety, cost-effectiveness, reduced contamination, and ecological strain. IM is the most satisfactory alternative protein source among all animal proteins and is beginning to be used more widely as research suggests it can replace a significant proportion of existing FM-based diets. Further investigation is needed to better understand the effects of inclusion of animal protein sources in aquaculture feeds on various fish species.

Conflicts of interest The authors declare no conflict of interest.

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