Fish Nutrition And Feed Development: Recent Innovation And Challenges

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Abstract
The importance of creating fish feeds that are both economical and nutritionally balanced has increased due to aquaculture's explosive growth as a key component of global food security. Research on the nutritional needs of cultured fish species and the development of sustainable substitutes for conventional feed ingredients like fishmeal and fish oil advanced significantly until 2015. The transition to plant-based proteins, animal byproducts, single-cell proteins, and early research into insect meals are highlighted in this paper, which examines the advancements and innovations in fish nutrition and feed development up to 2015. The use of functional additives such as probiotics, prebiotics, and immunostimulants, which enhance fish health, growth, and disease resistance, is another example of nutritional innovations. Extrusion and microencapsulation are two technological advancements in feed processing that have improved nutrient stability.
Notwithstanding these developments, the industry continued to face obstacles such as the anti-nutritional qualities of plant proteins, the decreased palatability and digestibility of substitute ingredients, and the ongoing reliance on limited marine resources. Progress was also hampered by environmental issues with eutrophication and nutrient waste, as well as financial and legal constraints on the use of new feed ingredients. However, the movement toward more effective and sustainable feeding practices signalled a significant shift in the field of aquaculture nutrition research. For researchers, feed producers, and aquaculture professionals searching for sustainable aquafeed solutions, this review provides a comprehensive resource.

Keywords: Fish nutrition, aquafeed, alternative protein sources, functional feed additives, fishmeal replacement, feed technology, aquaculture sustainability, fish health

I. Introduction

All living things depend on nutrition for growth, development, reproduction, and general health. Fish nutrition is a crucial aspect of aquaculture that has a direct impact on feed cost, fish health, production efficiency, and product quality. For aquaculture methods to be both sustainable and profitable, it is crucial to optimize the formulation of fish feed. As it has a direct impact on fish growth, survival, and the industry's overall sustainability, research on fish nutrition is essential to aquaculture development. Research aimed to improve production efficiency and lessen environmental impact by figuring out nutrient requirements, improving feed formulations, and investigating alternative protein sources. Gatlin's (2010) research on fish nutrition has repeatedly emphasized how crucial protein is for development and growth. Creating effective and economical feeds requires an understanding of the unique protein and amino acid needs of various species. Additionally, studies examined the function of vitamins, minerals, lipids, and carbohydrates in fish diets, focusing on how these nutrients affect growth, health, and resistance to disease. Research looked at the interactions between various nutrients, how they affect fish health overall, and how they affect their utilization (Gatlin, 2010).

A key component of aquaculture success is fish nutrition, which has a direct impact on the development, survival, and ability to reproduce of cultured species. The goal of this research is to create economically viable, ecologically friendly, and nutritionally balanced feeds that promote sustainable aquaculture methods. Determining the exact nutrient needs of several significant aquaculture species, such as milkfish, sea bass, Nile tilapia, and tiger shrimp, has been the subject of extensive research. These studies offer baseline information for realistic diet creation and improvement (Millamena, 1996). Depending on the species, the feed's protein content varies greatly. Carps need 25–35% protein, catfish 30–45%, and prawns 30–40%. Carp and catfish feeds normally need 6–8% fat, while prawn feed needs roughly 6%. Fat content is also essential. When creating feeds for finfish and shellfish, the precise needs for fatty and amino acids are crucial factors that affect the overall efficacy and quality of the feed (Paul & Giri, 2015). Optimizing fish's normal growth and overall production is directly related to feeding them a balanced diet. This emphasizes that in aquaculture, nutrition is important for increasing yield and efficiency as well as for survival (Paul & Giri, 2015). Future studies also take into account how feeds affect the environment, with the goal of creating environmentally friendly feeds and nutritional techniques to lessen the ecological footprint of fish farming (Millamena, 1996).

1.1 Overview of global fish production trends and the growing demand for sustainable feed

The world's population is expected to rise from 6.8 billion to roughly 9 billion by 2050. The demand for fisheries products from marine sources will rise as a result of this growth, which will also increase the need for wholesome food (Garcia & Rosenberg, 2010). Numerous factors, such as excessive fishing pressure, rising organic pollution, toxic contamination, coastal degradation, and climate change, are already seriously affecting the productivity of marine fisheries. These difficulties show that in order to satisfy future demand, sustainable practices are required (Garcia & Rosenberg, 2010).

Profit is the main factor influencing the patterns of fishery development, taking into account both expenses and income. After 1950, fisheries initially centred on species that ranged shallowly and were valued for their large body sizes, high catch potential, and high prices. Fishing grew to include less economically desirable species as the most lucrative opportunities were taken advantage of (Sethi et al., 2010). Between 1951 and 1999, the expected revenues from developed fisheries fell by 95%, which suggests that there were fewer high-catch or valuable fishing opportunities. Key indicators for comprehending the effects of harvest on ocean ecosystems are the economic characteristics of species (Sethi et al., 2010).

Only about 10% of fish are produced in territorial waters; the majority, about 90%, are produced by sea fishing. The need to boost aquaculture production to guarantee an adequate amount and quality of fish is growing as a result of changing demographic trends and a tendency for fisheries to decline (Costaiche & Niculae, 2014). Since fish do not need to maintain high body temperatures, intensive industrial fish systems have the economic benefit of low specific energy consumption (Costaiche & Niculae, 2014). By 2007, 68% of the world's fish production came from Asia, and by 2012, that number had risen to 73%. Fish production as a whole continued to rise in 2015, with aquaculture playing a major role. However, market-specific problems and economic considerations presented difficulties for the fish product trade. Although the provided text mostly concentrates on market trends rather than feed specifics, the growing reliance on aquaculture naturally indicates a growing need for sustainable feed solutions (Marcovecchio et al., 2015).

II. Nutritional Requirements of Cultured Fish Species

As they are either herbivorous or carnivorous, cultured fish species need a diet that is balanced in terms of macronutrients (proteins, lipids, and carbohydrates), micronutrients (vitamins and minerals), and essential amino and fatty acids. Optimizing these nutritional elements in fish feed to enhance growth and health was the main focus of research conducted between 2000 and 2015 (Fisheries, n.d.).

2.1 Macronutrients

For growth, energy, and other metabolic processes, organisms require macronutrients in comparatively large amounts. A valuable part of human nutrition, fish is high in macronutrients, mainly proteins and lipids (fats), with comparatively little carbohydrate. When ingested, these macronutrients are essential for both human and fish physiology.

i. Proteins: Growth, muscle development, and enzyme synthesis all depend on proteins. Protein needs vary among fish species and life stages. Chinook salmon, for instance, require 40% protein at 8°C and 55% at 15°C (Wilson & Halver, 1986). These are essential for development and many body processes. Depending on their age and feeding habits, fish may need anywhere from 30% to 55% of their diet to be protein (Millikin, 1982). A substantial amount of their nutritional makeup (15–24%) is made up of fish, which is a great source of high-quality animal protein (Wootton, 1992). All of the essential amino acids required for human growth and development are present in easily digestible fish protein. It is essential for immune system support, tissue growth and repair, and general health maintenance. Because of its biological and functional qualities, fish protein is also utilized in a variety of industries, such as pharmaceuticals and nutraceuticals (Wootton, 1992).

A. Essential amino acids: In aquaculture, essential fatty acids are vital nutrients that have a big impact on the consumer's makeup. Their significance goes beyond animal growth to include immunity, reproduction, and product quality. Arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine are essential amino acids, which are the building blocks of proteins (Millikin, 1982).

ii. Lipids: Also known as fats, lipids are a significant source of energy and are involved in how dietary protein is used. Fish prefer lipids as an energy source over carbohydrates because they are easily digested. In addition to being a concentrated source of energy, lipids can free up protein for growth instead of energy use. This protein-sparing effect has been observed in fish at dietary lipid concentrations as high as 12% to 24%. Linolenic acid (or its elongated forms in the w3 family) is frequently included in essential fatty acids for fish, and certain species also benefit from linoleic acid (Millikin, 1982). Fish can be classified as lean (less than 2.5%), medium-fatty (between 2.5 and 6%), or fatty (more than 6%). Fish use lipids as a major source of energy, and by designing their diet appropriately, their utilization can be maximized. Fish byproducts, like fish oil, are also excellent sources of nutrients and lipids (Wootton, 1992).

iii. Carbohydrates: Carbohydrates can be used as fuel and can spare protein, which means that they can lower the dietary requirement for protein. Especially for herbivorous and omnivorous species, carbohydrates are a vital source of energy. To save protein, they can also be added to the diets of carnivorous fish in slightly higher amounts than they would naturally consume (Millikin, 1982). Compared to proteins and fats, fish have comparatively few carbohydrates. In addition to being more affordable and easily accessible, carbohydrates can enhance the quality of the pellets used in fish feed (Wootton, 1992). Although they can use carbohydrates as fuel, fish typically prefer to use proteins. Depending on the species and diet, fish can have different amounts of carbohydrates (Wootton, 1992)..

2.2 Micronutrients

Micronutrients are nutrients that are needed in smaller amounts but are just as important for good health and normal body processes. Minerals and vitamins are among them (Millikin, 1982).

i. Vitamins

Numerous metabolic processes depend on these organic compounds. Thiamine, riboflavin, pyridoxine, niacin, pantothenic acid, ascorbic acid, choline, folic acid, cyanocobalamin, biotin, inositol, vitamin A, cholecalciferol (vitamin D), vitamin E, and vitamin K are among the vitamins that fish need (Millikin, 1982). In general, fish is a good source of B vitamins. Fatty fish species are also noteworthy for their high vitamin A and D content.

ii. Minerals

Enzyme activity, bone formation, and other physiological functions depend on these inorganic elements. Phosphorus, magnesium, trace amounts of manganese, zinc, iron, copper, selenium, and iodine are among the minerals that fish need to eat (Millikin, 1982). A wide variety of minerals can be found in fish. These consist of iron, zinc, magnesium, and phosphorus. Iodine can also be found in marine fish. Calcium, a vital component of bones and teeth, also plays a role in nerve transmission and muscle contraction (Lall & Dumas, 2015). Zinc promotes cell division, wound healing, and immunological response. Iodine is required for the synthesis of thyroid hormones, which control metabolism. Hemoglobin, which transports oxygen throughout the blood, contains iron (Achionye-Nzeh & Adedoyin, 2011). Phosphorus is Vital for energy production and bone health. Selenium is an antioxidant that aids in the production of thyroid hormones and shields cells from harm (Achionye-Nzeh & Adedoyin, 2011).

iii. Fatty acids

Omega-3 fatty acids, such as EPA and DHA, are found naturally in fish oil and are critical to the health and welfare of fish (Millikin, 1982). It has been demonstrated that the majority of aquaculture species receive EFA value from all five fatty acids (DHA, EPA, ARA, LNA, and LOA); however, species-specific differences exist in the ideal levels of dietary inclusion, the ratio of n-3 to n-6 classes, and chain lengths (18-, 20-, or 22-C)(Glencross, 2009). Omega-3 fatty acids, such as EPA and DHA, which are critical for brain health, heart disease prevention, and general well-being, are especially abundant in fish fats (Wootton, 1992).

2.3 Species-specific nutritional needs

Depending on whether they are herbivorous, carnivorous, or omnivorous, fish have quite different nutritional needs. In general, carnivorous fish need 40–55 percent more protein in their diet than herbivorous and omnivorous fish (25–35 percent). This is because herbivores and omnivores use carbohydrates more effectively than carnivores, who use protein as their main energy source (Gatlin, 2010).

2.3.1 Carnivorous fishes: Fish that are carnivorous need diets high in protein and frequently require particular fatty and amino acids that are present in foods derived from animals (Fisheries, n.d.). Since they depend on protein for energy and tissue growth, carnivorous fish, such as salmon and trout, have a higher protein requirement (40–55%) (Gatlin, 2010). Carbohydrates, which are frequently present in plant-based diets, are harder for them to digest and use. For instance, research on rainbow trout revealed that, in accordance with the FAO, the digestion of carbohydrates declines as dietary carbohydrate levels rise above 20% (*Training Manual on Marine FinFish Netcage Culture in Singapore*, n.d.).

2.3.2 Herbivorous fish: Compared to carnivores, herbivorous fish may require more fibre and carbohydrates (Fisheries, n.d.). Carp and tilapia are examples of herbivorous and omnivorous fish that typically require diets that contain 25–35% protein. These fish can effectively use carbohydrates as fuel, freeing up protein for growth and other purposes (Gatlin, 2010). For Illustrations According to Jauncey (2000), Tilapia studies have demonstrated that growth and yield can be enhanced by raising dietary lipid and carbohydrate levels while lowering protein levels. According to Clements et al. (2009), herbivorous fish are essential to reef ecosystems because they affect biodiversity and carbon flux. They require a balanced intake of carbohydrates, proteins, and essential fatty acids, with a focus on the nutritional quality of their algal diets(Clements et al., 2009). According to Clements et al. (2009), these fish have developed specialized digestive systems that are less effective than carnivorous diets at extracting nutrients from fibrous plant materials.

2.3.3 Omnivorous fish: Fish that are omnivores may have more adaptable nutritional requirements and can use a greater variety of nutrients (Fisheries, n.d.). A wider range of nutrients can be consumed by omnivorous fish because they can adjust to a variety of diets that include both plant and animal sources (Millikin, 1982). Compared to strict carnivores, they are more adaptable to dietary changes because their diets usually consist of a combination of proteins, carbs, and fats (Millikin, 1982).

3. Traditional Fish Feed Ingredients

Concerns about overfishing, sustainability, and cost have been raised by aquaculture feeds' reliance on fishmeal and fish oil. The demand for substitute feed ingredients has grown significantly as aquaculture keeps growing. The environmental effects of traditional fish-derived components and the need for more sustainable industry practices are the driving forces behind this shift. Because of their high protein and lipid content—both of which are essential for fish growth and health—fishmeal and fish oil were the preferred ingredients in fish feed (Fisheries, n.d.). Essential fatty acids, such as omega-3s, a balanced amino acid profile, and a number of vitamins and minerals are all found in fishmeal. Fish feed became more costly as a result of the increase in demand for fishmeal and fish oil brought on by the growth of aquaculture (Fisheries, n.d.). The biggest expenses for fish farmers are fishmeal and fish oil, whose prices vary because of the high demand and limited supply (Friesen, 2008).

The goal of looking for substitute ingredients is to lower these expenses without sacrificing fish health or feed quality (Friesen, 2008). Concerns regarding overfishing and the sustainability of marine ecosystems were raised by the dependence on wild-caught fish for the production of fishmeal and fish oil (*Fish Feed: Why We Need Sustainable Alternatives*, n.d.). The search for sustainable alternatives has been spurred by overfishing and habitat destruction associated with the production of fishmeal and fish oil (Watanabe, 2002). Research shows that adding different protein sources, like plant proteins and poultry byproducts, can have little detrimental impact on fish growth (Friesen, 2008). Some fish populations declined as a result of the intense fishing pressure for fish used to produce fishmeal, which further reduced the supply of these feed ingredients.

Research efforts to find and assess substitute ingredients for fish feed grew in response to these constraints. In order to lessen or replace fishmeal and fish oil, this involved investigating plant-based proteins, insect meal, algae-based oils, and other sustainable sources (Fisheries, n.d.).. Research aimed to replace fishmeal in fish feed formulations with plant-based protein sources such as rapeseed meal, soybean meal, and others. Although fishmeal and fish oil continued to be crucial ingredients in many aquaculture operations, there was a growing awareness and adoption of more sustainable fish feed options by the end of the period.

4. Innovations in Fish Feed Development

To enhance fish health and farming efficiency, a number of formulations have been developed that combine traditional ingredients with contemporary nutritional science. Finding sustainable substitutes for fishmeal, enhancing feed digestibility and nutrient utilization, and creating more effective feed processing methods were the main goals of fish feed development. The use of insects as a source of protein, the effects of various feed formulations on fish growth and health, and the possibilities of biofloc technology were also investigated (Wu, 2014). In order to improve digestion and growth rates, modern feeds include a range of ingredients, including soybean meal, cottonseed meal, and herbal additives (Shaoqiang, 2014). Feeds with particular proportions of proteins, fats, and carbohydrates that are suited to the dietary requirements of various fish species, including tilapia and milkfish, are examples of innovations (Millamena, 1993).

4.1 Alternative Protein Sources

Soybean meal, corn gluten meal, and pea proteins are other protein sources in fish feed, particularly plant-based alternatives. Fishmeal, an animal protein source, is increasingly being substituted with these ingredients in aquaculture feed. The growing expenses and environmental issues surrounding conventional fishmeal have accelerated the search for substitute protein sources for fish diets. Plant-based proteins have become a good alternative, especially pea proteins, corn gluten meal, and soybean meal. These substitutes support sustainable aquaculture methods in addition to offering necessary amino acids

4.1.1 Plant-based proteins

In aquaculture diets, plant-based proteins like pea protein, corn gluten, and soybean meal are being investigated more and more as potential substitutes for fish meal. According to research, these plant-based sources can successfully substitute fish meal without materially affecting the health or growth performance of different fish species (Hansen et al., 2006). Pea protein can replace up to 25% of fish meal without negatively affecting immunological response, body composition, or growth performance. Strong tolerance to these ingredients was demonstrated by the maintenance of high growth rates with up to 440 g/kg of plant protein (Hansen et al., 2006). Growth was at its best when 20% of fish meal was substituted with a plant protein mixture; higher substitutions resulted in less weight gain and less feed efficiency (Qihui et al., n.d.).

i. **Soybean Meal:** A common plant protein source in fish and other animal feeds is soybean meal. Although it may be lacking in some essential amino acids, such as methionine, it is renowned for having a high protein content and a good amino acid profile (Shahkar et al., 2011). Diets containing soybean meal, either by itself or in conjunction with other plant proteins, have shown a high level of tolerance for Atlantic cod. Even when plant proteins made up a sizable amount of the diet—up to 440 g kg^{-1} of plant ingredients—fish were still able to sustain growth rates by increasing their feed intake (Hansen et al., 2006). Numerous fish species can successfully substitute soybean meal for some of their fish meal, according to studies. For example, substituting soybean meal (along with corn gluten) at up to 15% of fish meal did not substantially impact the growth performance of Rutilus frisii kutum fingerlings (Shahkar et al., 2011).

ii. **Corn gluten:** Another plant-based protein concentrate that is frequently utilized in animal feed is corn gluten meal. As a byproduct of wet-milling corn, it is high in protein but generally lower in tryptophan and lysine than fish or soybean meal (Shahkar et al., 2011). Corn gluten meal, when mixed with soybean meal, could replace significant amounts of fish meal (up to 15%) without adversely affecting growth performance, according to research on Rutilus frisii kutum fingerlings (Shahkar et al., 2011).

iii. **Pea Protein:** In fish feed, legumes like peas are being investigated as a potential substitute for fishmeal because they are also high in protein (Hansen et al., 2006). Pea protein, which is usually made from yellow peas, is becoming more and more popular as a sustainable protein source. It has a high protein content and does not contain any of the common soy allergens (Shahkar et al., 2011). Although it can be limiting in methionine, it is generally thought to have a balanced amino acid profile. For a number of fish species, pea protein has demonstrated promise in replacing fish meal in diets, frequently producing similar growth performance and feed utilization (Shahkar et al., 2011).

4.1.2 Animal byproducts

Blood meal and poultry byproduct meal (PBM) are utilized as protein sources in fish feed, successfully substituting for or enhancing fishmeal (Samaddar et al., 2015). These byproducts can be suitable substitutes for fishmeal, sometimes with extra advantages, according to research by Samaddar et al. (2015) on the ideal inclusion levels in different fish species. They are becoming more and more acknowledged as good sources of protein for fish feed, especially in aquaculture. These components meet the rising demand for sustainable aquafeeds by providing an affordable substitute for conventional fishmeal. PBM is a byproduct of processing poultry, which includes undeveloped eggs, legs, necks, and intestines that have been ground, rendered, and cleaned. It is a good source of vitamins, minerals, fatty acids, essential amino acids, and protein (Samaddar et al., 2015). According to studies by Hernandez et al. (2014), PBM can effectively replace fishmeal in the diets of a variety of marine fish species, such as red seabream, gilthead seabream, and black seabass. In certain situations, lysine and methionine supplements—amino acids that can be limiting in PBM—are required to attain the best possible growth. According to research, PBM can replace up to 50% of fishmeal without adversely affecting some species' growth (Hernandez et al., 2014). A common ingredient in aquafeed is blood meal, a dry product made from fresh, clean animal blood. It can add to the feed's mineral content and is a great source of protein (Samaddar et al., 2015). Studies have looked into using blood meal as a supplement or replacement for fishmeal in fish feed, with some determining the ideal levels of inclusion for growth. According to one study, adding 10–15% blood meal to fish feed can give them the right amount of nutrients for improved growth. Additionally, studies have looked into replacing fishmeal with fermented mixtures of fish offal and blood, with some success (Samaddar et al., 2015).

4.1.3 Single-cell proteins

Proteins obtained from the cells of different microorganisms, such as bacteria, fungi, yeast, and algae, are referred to as single-cell proteins (SCPs). These microbes are grown on a variety of carbon sources to produce protein. These microorganisms can be eaten in their entirety or their harvested, dried cells (Najafpour, 2007).In aquaculture, single-cell proteins (SCP) made from bacteria, yeast, and microalgae have become competitive substitutes for conventional protein sources, especially when it comes to fish diets. In addition to other applications, such as human food supplements, SCP is used as a source of protein for animal feed. Because SCP can be produced in large quantities quickly, it has great potential to alleviate the world's food shortages, particularly as the world's population grows (Najafpour, 2007). According to research by García-Garibay et al. (2014), these microbes can improve fish growth and nutrient digestibility, making them a viable way to meet the world's growing protein needs. Two important microorganisms involved in the synthesis of single-cell protein (SCP) are yeasts and bacteria. Bacteria are commonly used to produce feed, including possibly fish feed, whereas yeasts are mainly used for human consumption.

When it comes to feed applications, bacteria have a number of benefits over yeasts, including higher protein content, higher yields, and faster growth rates. They are effective at producing biomass for animal feed because of these qualities (García-Garibay et al., 2014). The high concentration of nucleic acids and cell wall components in SCP, whether from bacteria or yeast, is a significant barrier to its consumption. These factors may limit the protein's direct absorption in the diet, requiring processing to separate the protein before use (García-Garibay et al., 2014).

Due to their rich nutritional makeup, especially their high protein content and advantageous amino acid profiles, marine microalgae present a promising alternative as a fish feed source. They are therefore a viable option for aquaculture applications involving Single Cell Proteins (SCP) (Fábregas & Herrero, 1985). It is known that marine microalgae species like Chlorella stigmatophora, Isochrysis galbana, Dunaliella tertiolecta, and Tetraselmis suecica are excellent biological sources of Single Cell Protein (SCP). Dunaliella tertiolecta has the highest protein levels, although their protein content varies greatly, making up 39.12% to 54.20% of their dry matter. These protein levels are on par with or even higher than those found in certain freshwater microalgal species. Less than 7% of the dry matter of marine microalgae is made up of nucleic acids (Fábregas & Herrero, 1985). This is significantly less than that of bacteria (9%–22%) and yeasts (8%–12%), two other common sources of SCP. As high levels of purines (from nucleic acid metabolism) can cause health problems like gout in humans and other mammals, a lower nucleic acid content is advantageous (Fábregas & Herrero, 1985).

4.1.4 Insect meal

In aquaculture, black soldier fly (BSF) larvae are a viable substitute for fishmeal, demonstrating their potential as a sustainable and wholesome feed source. The meal of Black Soldier Fly (BSF) larvae is being investigated as a sustainable substitute for fishmeal in aquaculture diets. It has much potential, particularly for organic aquaculture feeds (Stamer et al., 2014). As it can be raised on a variety of organic waste materials, the black soldier fly (Hermetia illucens) is regarded as a perfect candidate for insect-based feeds. BSF larvae can produce biomass that is high in protein (about 42%) and fat (up to 35%) while reducing the amount of organic waste by up to 50%. They are therefore a valuable feed ingredient (Stamer et al., 2014). One of the most promising emerging methods is the culture of BSF larvae for use as fish feed. This method has the added advantage of utilizing organic waste and offers a potential solution for the safe management of manure for both humans and animals (Rana et al., 2015). The BSF larvae have an extremely high nutritional content. BSF larvae had a dry matter content of 40–45% protein, 30–35% fat, 11–15% ash, 4.8–5.1% calcium, and 0.6% phosphorus, along with a variety of minerals and amino acids (Rana et al., 2015).

4.2 Lipid Source Alternatives

Algal oils provide DHA and EPA, two essential fatty acids, to preserve nutritional value in fish feed, while plant oils like canola and linseed can partially replace fish oil. Historically, the main lipid source in Atlantic salmon feed has been fish oil. However, there is increasing interest in alternative lipid sources as a result of growing aquaculture production and the scarcity of marine raw materials (Moldal et al., 2014). These substitutes for fish oil can be either full or partial and include plant and algae oils. There are financial and environmental benefits to using plant-based ingredients in fish feed. There is much interest in substituting vegetable oils for fish oil from an economic and sustainability standpoint (Moldal et al., 2014).

Rapeseed (Canola) Oil, which is a vegetable oil, is known to be rich in monounsaturated fatty acids and can be used as a substitute lipid source in aquaculture feeds (Turchini et al., 2010). Soybean Oil Packed with n-6 polyunsaturated fatty acids, soybean oil is another important plant-based substitute (Turchini et al., 2010). Additional Vegetable Oil Other n-6 and n-3 polyunsaturated fatty acid-rich vegetable oils and blends are also mentioned in passing as possible substitutes in the paper. Although linseed (flaxseed) oil is a well-known n-3 rich vegetable oil, it is not mentioned explicitly in the text that is provided; instead, it is included in the more general category of vegetable oils that are rich in n-3 polyunsaturated fatty acids (Turchini et al., 2010).

Algal oils, which are frequently included in this category, are becoming more and more valued as alternatives to fish oil for supplying these vital fatty acids in aquaculture feeds due to their high content of DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid). The growing demand for aquaculture products and the limited supply of fish oil have prompted research into different alternative lipid sources. The aquaculture industry's sustainability depends on these substitutes, which include plant oils and innovative n-3-rich sources like algal oils. Their goal is to preserve the nutritional value of farmed fish while lowering dependency on marine resources (Turchini et al., 2010). Due to dwindling marine oil supplies worldwide, the aquaculture sector is aggressively looking for substitute lipid sources for fish feed. In the diets of species like gilthead seabream, vegetable oils, like linseed oil, have been studied as partial replacements for fish oil (Wassef et al., 2009).

4.3 Functional Feeds

To improve fish health, stress reduction, disease resistance, and growth, aquaculture uses functional feeds that contain immunostimulants, prebiotics, and probiotics. Immunostimulants are chemicals that actively stimulate the immune system; they are also referred to as immunomodulators, adjuvants, or biological response modifiers (Ganguly et al., 2010). They can be given as nutrients or medications. Immunostimulants generally increase fish and crustacean immunity when given as dietary supplements, even in tiny amounts. Better disease resistance is a result of this increased immunity (Ganguly et al., 2010). It concentrated on how these supplements can enhance fish performance by strengthening the immune system, encouraging good gut flora, and enhancing nutrient absorption (Akhter et al., 2015). When consumed, probiotics—live microorganisms—can colonize the gut and enhance the health of the host. Probiotics can boost immune responses, improve nutrient digestion, and compete with dangerous bacteria. For instance, probiotics based on Bacillus have demonstrated promise in aquaculture for enhancing disease resistance, feed conversion, and growth (Akhter et al., 2015).

Fish kept in intensive culture are more vulnerable to environmental stressors like hypoxia and poor water quality, as well as parasites and infectious diseases (Oliva-Teles, 2012). Economic losses result from these stressors' detrimental effects on fish health and performance. Although stress can be reduced with effective management techniques, people are still more vulnerable in crowded settings (Oliva-Teles, 2012). Fish fed dietary nano-sized RNA grew considerably more than those fed bare RNA or chitosan alone. The study assessed growth rate and other aspects of productive efficiency and discovered that RNA-loaded chitosan NPs raised viscerosomatic and hepato-indices (Ferosekhan et al., 2014). Research indicates that fish health and disease resistance can be improved by diets overfortified with particular nutrients, even at levels above the bare minimum. These nutrients consist of vitamins, minerals, essential fatty acids (FAs), and amino acids (Oliva-Teles, 2012). The disease resistance of fish fed nano-sized RNA was noticeably higher. In aquaculture, where disease outbreaks can result in significant losses, this is especially crucial (Ferosekhan et al., 2014).

4.4 Nutrigenomics

The study of nutrigenomics examines the profound effects of diet on fish metabolism and immunological responses, as well as the ways in which nutrients and bioactive food compounds influence gene expression. Research on blue catfish, for example, emphasizes the vital connection between immunity and nutrition, especially where pathogens attach and enter (Li et al., 2014). It is commonly acknowledged in nutrigenomics that feeding factors have a major influence on the expression of related genes in aquatic animals. Given that fish have stress reactions and a sense of nociception similar to mammals, this knowledge is essential for enhancing the welfare of farmed aquatic animals (Exadactylos, 2014). Feed Deprivation on Gene Expression on biological and physiological repercussions are both wild and farmed fish frequently experience brief periods of feed deprivation as a result of reproductive processes, seasonal temperature fluctuations, or disease outbreaks. Fish that fast may experience serious physiological and biological effects (Li et al., 2014). Fasting has a significant effect on mucosal immunity, which can change the host's vulnerability to infections. A short 7-day fast was found to change 530 genes in the surface mucosa of blue catfish (Li et al., 2014).

5. Feed Formulation and Processing Technologies

Technologies for feed formulation and processing are essential to the manufacturing of animal feeds, especially for the livestock and aquaculture sectors. These procedures entail a complex interaction of nutritional science, ingredient properties, and technological developments to produce feeds that maximize growth, health, and feed efficiency (P et al., n.d.). In the study by Bai et al. (2012), the procedure is initiated by weighing raw plant materials with a moisture content of 15–40% by weight as the first step in the process. After that, the material is sent to a pulverizer, where it is crushed into particles larger than 0 mm but smaller than 3 mm. After being crushed, the material is moved to the mixing apparatus. A water pump is then used to introduce the slurry under pressure into this apparatus, where it is evenly mixed with the crushed material to create a combined material. After that, the mixture is placed in a drying apparatus to dry gradually. The drying apparatus maintains a temperature range of 300–500 degrees Celsius at the feed inlet and 60–90 degrees Celsius at the discharge outlet.The feed made with this technology is distinguished by its suitable particle size and shape, as well as its pleasant flavour. Additionally, the procedure effectively eliminates bacteria, viruses, and heavy metals. The final feed is intended to increase animal appetite, increase the effectiveness of feed absorption, and safeguard the health of the animals (Bai et al., 2012).

5.1 Extrusion techniques, Pellet stability, and Digestibility improvement.

The stability and digestibility of fish feed have been greatly improved by developments in extrusion techniques, meeting aquaculture's nutritional requirements and sustainability goals. In addition to increasing the digestibility of different feed ingredients, extrusion processing improves the feed's physical characteristics, including its floatability and water stability. The apparent digestibility coefficients (ADCs) of dry matter, crude fat, and gross energy in rainbow trout feed ingredients were found to be considerably improved by extrusion processing (Cheng & Hardy, 2003). The main technique for creating aquafeeds is extrusion cooking, which significantly enhances the physical characteristics of the feed as well as the growth and digestibility of fish (Ayadi et al., 2012). Due to their wider conveying angles and self-wiping capabilities, twin-screw extruders—which gained popularity in the 1970s—offer advantages over single-screw extruders and can process a greater range of ingredients. Controlling pellet density through extrusion improves durability, water stability, production efficiency, and adaptability (Ayadi et al., 2012).

On the other hand, the study found that extrusion decreased the ADCs of zinc, copper, iron, phosphorus, and crude protein. The particular ingredients used determined how extrusion processing affected the chemical composition and nutrient ADCs. This implies that not all feed components experience the same advantages or disadvantages from extrusion (Cheng & Hardy, 2003). Water stability, which is determined by how long a pellet stays intact in water, is a crucial quality metric for fish feed. It measures the amount of time that dissolves and the amount of nutrients that are lost when exposed to water (Ayadi et al., 2012). In order to guarantee that the feed is available for fish consumption prior to disintegration, longer water stability times indicate high physical stability of extrudates (Ayadi et al., 2012).

To survive feeding, stacking, and transportation, premium fish feed extrudates need to be robust. By calculating the quantity of fines generated following tumbling under controlled circumstances, PDI measures this durability (Ayadi et al., 2012). Coating fish feed pellets with particular enzymes or an emulsion can improve their digestibility. Fats and oils, an emulsifier, and the selected enzyme are used to create this emulsion (Park et al., 2009). The main objective of this approach is to increase fish growth rate and lessen environmental contamination by reducing fish waste because of improved digestibility. To help with digestion, this coating process can make use of a variety of enzymes (Park et al., 2009).

5.2 Coated feeds and microencapsulation of nutrients and drugs

Aquatic animal nutrition uses coated feeds and microencapsulation techniques to deliver nutrients and bioactive agents efficiently. The goal of these techniques is improved absorption and targeted release in the digestive system (Tandler et al., 2006). In order to enhance the delivery and efficacy of nutrients, medications, or other materials in fish diets, microencapsulation and coated feeds are used in fish farming. This method reduces nutrient leaching, shields delicate components from deterioration, and may improve the overall nutritional content and health advantages of fish feed (Luzardo-Alvarez et al., 2010). By encasing a core material (drugs, nutrients, etc.) in a coating material, microencapsulation produces tiny capsules. Fish nutrient utilization is improved by reduced leaching, which stops water-soluble nutrients from escaping into the surrounding water. Restricted release enhances the absorption and efficacy of nutrients or medications by enabling their gradual release over time. Protection prevents delicate ingredients from deteriorating as a result of exposure to light, oxygen, or high temperatures (Luzardo-Alvarez et al., 2010). Specific delivery can be made to target specific parts of the fish's digestive system with drugs or nutrients (Luzardo-Alvarez et al., 2010). Several essential elements are usually present in an encapsulated formulation intended for the delivery of food and bioactive agents to aquatic animals: i) The nutrients, vital food ingredients for the development and well-being of the animal, ii) Enhancers of Digestion, substances that facilitate food digestion and absorption, iii) Bioactive substances with a biological impact, like probiotics, hormones, and medications and iv)Enhancers of Local Absorption Agents that enhance the absorption of chemicals in the digestive tract regions (Tandler et al., 2006).

6. Challenges in Fish Nutrition and Feed Development

Finding sustainable and affordable protein sources, controlling the nutritional requirements of various fish species, especially during the larval stages, and making sure feed is stored optimally to preserve nutrient quality were the main challenges in fish nutrition and feed development. Concerns were also raised regarding the effects of specific feed ingredients on the environment and the necessity of more effective feed utilization in order to minimize waste (Hixson, 2014). Fishmeal, a limited resource with a potentially unsustainable production capacity, was a major component of traditional fish feed (Trushenski et al., 2006). Alternative protein sources, such as microbial (single-cell protein) and plant-based (soybeans, oilseeds, etc.), were the focus of research (Trushenski et al., 2006). Anti-nutritional elements found in plant-based proteins can impair fish health and growth. To lessen these problems, methods such as genetic modification, enzyme supplementation, and processing were investigated. Concerns regarding competition with the human food supply and possible increases in land and water use were also raised by the use of plant-based ingredients (Trushenski et al., 2006).

The main challenges in the development of aquaculture feed differ greatly among farmers, nations, and geographical areas. The goal of the farming activity, the planned production system, the market value of the cultured species, and the farmer's access to and cost of resources are some of the variables that affect this variability (Tacon & Barg, 1998). Finfish have evolved across almost every conceivable niche, feeding strategy, trophic level, and habitat, and they exhibit a wide range of nutritional requirements. Terrestrial livestock, on the other hand, usually have more consistent nutritional needs (Trushenski et al., 2006). Currently, capture fisheries are the primary source of inputs for farming systems that raise marine and diadromous finfish and crustaceans (MDFC) (Tacon & Barg, 1998). Finfish nutrition is limited by the aquatic environment itself. Fish are typically poikilothermic, which means that their body temperature fluctuates in response to their surroundings. This has a significant impact on their bioenergetic regimes and, consequently, their nutritional needs. Compared to homeothermic terrestrial animals, which have a limited homeostatic temperature range, this is a substantial difference (Trushenski et al., 2006).

7. Sustainability and Environmental Concerns

Minimizing the environmental impact of aquaculture requires sustainable practices, especially when it comes to the composition and life cycle of the feed. One of the main priorities is the creation of environmentally friendly feeding practices and low-pollution feeds (Nichols & Quesada, 2011). Creating feed compositions that substitute conventional, less sustainable ingredients is a key component of sustainable aquaculture. For example, alternative sources of eicosapentaenoic acid (EPA) and, optionally, docosahexaenoic acid (DHA) can be used in place of fish oil, a common ingredient in aquaculture feeds, either completely or partially (Nichols & Quesada, 2011). Fish oil and fish meal have historically been the main components of aquafeeds. However, at the current levels of usage in feed formulations, the production of these conventional ingredients worldwide is not enough to sustain aquaculture's continued growth. This restriction presents the industry and researchers with opportunities as well as challenges to investigate and use substitute ingredients (Hardy, 2009). The need for more aquafeed and, as a result, the creation of sustainable substitutes is further highlighted by the growing demand for aquaculture production, which provides half of the fisheries products consumed each year (Hardy, 2009).

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8. Conclusion

Aquaculture's quick growth as a means of ensuring food security worldwide has made the creation of sustainable and nutrient-dense fish feeds necessary. Understanding the nutritional needs of cultured fish species and finding workable substitutes for conventional feed ingredients like fishmeal and fish oil were major advancements up until 2015. The use of single-cell proteins, plant-based proteins, animal byproducts, and early-stage insect meals presented encouraging opportunities to lessen reliance on limited marine resources. Feed quality, nutrient stability, and digestibility were further improved by technological advancements like extrusion and microencapsulation. Furthermore, the addition of functional additives such as immunostimulants, probiotics, and prebiotics enhanced fish growth, health, and disease resistance. Widespread adoption was hampered by problems like decreased feed palatability, anti-nutritional qualities in plant ingredients, and the financial and legal constraints associated with new ingredients. Significant obstacles were also presented by environmental issues, particularly those pertaining to eutrophication and nutrient waste. Notwithstanding these obstacles, aquaculture feed development generally moved in the direction of increased efficiency, innovation, and sustainability. In order to improve feed formulations, protect the environment, and provide aquaculture species with cost-effective and environmentally responsible nutrition, this review emphasizes the significance of ongoing research and cross-sector collaboration.

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