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Review

The role of nutrition in achieving more sustainable and environmentally friendly aquaculture

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ABSTRACT – Sustainability applies to almost all aspects of human activity, and the ever-growing aquaculture industry is no exception. Feeding aquatic animals is of paramount importance in terms of economic and environmental sustainability. This review discusses practices and promising new results for improving feed efficiency at different levels of production intensity. Special emphasis is placed on demonstrating how semi-intensive pond technology can be considered *ab ovo* sustainable also from a social point of view. Recent achievements in the field of alternative protein sources to replace fishmeal are also discussed, as well as the beneficial properties of special feed additives such as probiotics and phytochemicals.

Keywords: aquaculture, sustainability, nutrition

INTRODUCTION

The concept of sustainability has become a prominent buzzword in the field of research and development, and with good reason, as it relates to almost all aspects of human activity and has implications for the future of our planet. However, reviewing the core principles of sustainability from an aquaculture perspective may be useful. The primary objectives of sustainable aquaculture are to produce food to minimize adverse environmental impacts and promote social and economic well-being. The following key principles are worth noting:

- *Environmental Sustainability* - Natural habitat disruption should be kept to an absolute minimum, responsible waste management practices should be used, water quality should be protected, and biodiversity should be conserved.
- *Economic Sustainability* – Key issues are: efficient production, fair trade, community development.
- *Social sustainability* - Labour rights and community involvement are involved.
- *Animal welfare issues*

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Specific practices for sustainable aquaculture include recirculating aquaculture systems (RAS)., integrated aquaculture with agriculture or livestock, organic aquaculture, and using sustainable feed sources. Integrated multi-trophic aquaculture (IMTA) represents an approach to sustainable aquaculture that involves farming species from different trophic levels in a single system (Fang et al., 2016). The system offers both environmental and economic benefits, including improved nutrient cycling, reduced environmental impact, and increased profits (Granada et al., 2016). IMTA can be applied in freshwater, brackish, and marine environments, with various approaches tailored to local conditions (Azhar and Memiş, 2023). Research has shown that IMTA can enhance sustainability in aquaculture by reducing nutrient outputs, improving resource utilization, and potentially increasing public acceptance of aquaculture operations (Granada et al., 2016). It should be noted that traditional semi-intensive fishpond polyculture, although it is not usually assigned to this category, is also essentially an IMTA. Furthermore, the polyculture of giant freshwater prawn, silver, and bighead carp with freshwater pearl mussel and silver and bighead carp has also demonstrated considerable promise in inland ponds (Tang et al., 2024). Similarly, the cultivation of mussels and seaweed in a biculture has also yielded favourable results (Michler-Cieluch and Kodeih, 2008). This category also encompasses aquaponics, in which the waste produced by farmed fish or other aquatic creatures is used to nourish plants grown hydroponically. The automatic recirculating system allows the purification of water, which is then used again for the next cycle. Aquaponics requires little monitoring or measuring, making it a relatively simple and low-maintenance system.

Further detailed and pertinent general information on sustainable aquaculture can be found in several publications, including those by Costa-Pierce (2002), “SustainAqua” (2009), Shepon et al. (2021), Austin et al. (2022), Pounds et al. (2022), Barbosa et al. (2024), Garlock et al. (2024), Keer et al. (2024), Tucciarone et al. (2024) and Zhang et al. (2024) which all discuss the object from a different point of view.

While economic sustainability remains a primary objective, all other criteria mentioned above must also be considered to achieve sustainability in aquaculture. Pursuing continuous improvement in production methods is imperative while simultaneously reducing their environmental and energy footprint. The nutritional requirements of the cultured species are undoubtedly a crucial factor in this regard. The objective of this review is to identify the principal elements of nutrition and feeding technology that can facilitate the enhancement of the sustainability and environmental friendliness of the aquaculture industry, while simultaneously promoting economic sustainability. The optimization of feed efficiency represents a pivotal concern in animal production, given that feed constitutes a substantial proportion of overall costs. Fortunately, economic and environmental protection objectives are aligned in this case, thereby promoting sustainability. The objective of this study was to conduct a review of the principal fields of feeding and feed development and manufacturing related to aquaculture's sustainability.

TECHNOLOGICAL METHODS OF FEEDING USED TO IMPROVE FEED EFFICIENCY

Rational feed development and feeding practice are based on a thorough understanding of the nutritional requirements of cultured animals. The nutritional requirements of aquatic animals, being poikilothermic organisms, require consideration of factors that differ from those applicable to warm-blooded (homeothermic) animals. The temperature of the water in which the animals are kept is a significant factor in their metabolism, which in turn affects their energy requirements and therefore their feed intake. It is also important to consider the age of the animals, as this affects their growth rate in a similar way to homeothermic organisms. It is also important to consider the age of the animals, as this affects their growth rate. Figure 1. depicts the theoretical relationship between feeding level, growth rate, and feed conversion, which collectively determine the efficacy of production.

To optimize feed efficiency, it is indispensable simultaneously to meet both qualitative and quantitative nutrient requirements. The primary objective of the aquaculture industry is to develop the most economically viable feed that meets the nutritional requirements of a given age group of cultured species. Other key considerations are reducing feeding costs and improving water quality through optimal feeding technology. It is essential to minimize feeding loss, which includes both the indigestible portion and all metabolic losses. However, it is important to remember that a non-negligible amount of the offered feed is typically uneaten. The proportion of uneaten feed varies considerably, but an average of 10% has been estimated (Craig, 2009). Commercial feed pellets must remain intact in water until consumed, which is especially important for slow-feeding aquaculture species such as shrimp (Lovell, 1991). Extrusion can be an alternative process for aquaculture feed production, increasing digestibility, and functional properties of the aquaculture feed, such as water stability and floatability. The thermal process during extrusion decreases the antinutritional factors present in legumes or other agro-industrial by-products, such as trypsin inhibitors and lectins. The beneficial effects of extrusion are detailed by Delgado and Reyes-Jaquez (2018). The use of binders as feed additives to ensure water stability has been a standard practice for some time (Tacon, 1987).

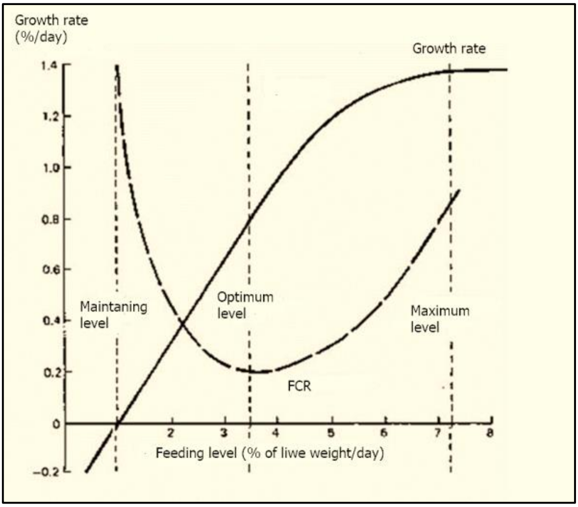

Figure 1. Correlation between feeding level, growth rate, and feed conversion ratio (Modified after *Lovell*, 1998)

However, this does not address all issues related to feed loss. It is crucial to identify the optimal feeding frequency to minimize this direct loss and improve the feed conversion ratio (FCR). To this end, published feeding rate tables are available for the majority of commonly cultured species (Craig, 2009). In the current market, there is a wide range of automatic feeders available for programmed feed delivery in cages, raceways, ponds, and RAS operations. These can help to ensure optimal feeding. In the future, monitoring systems could play a significant role in optimizing feeding regimes by providing information about actual feed loss. This is an area that has been explored by Parra et al. (2018). It is also essential to consider the key issues of nutrient sensing and feeding stimulation in this context (Hancz, 2020).

The frequency of feeding was proven to have a significant effect on the growth, feed conversion, and even reproductive performance of different fish species. Optimal growth and feed utilization of juvenile Nile tilapia was achieved by providing food four to five times per day (Daudpota et al., 2016).

In contrast, rainbow trout *(Oncorhynchus mykiss)* showed the greatest food intake and growth with only two feedings per day, with minimal effect on body composition (Grayton and Beamish, 1977). Two feedings per day were found to be optimal for the growth and reproductive performance of the ornamental Siamese fighting fish *(Betta splendens)* (James and Sampath, 2004). Juvenile estuarine groupers *(Epinephelus salmoides)* exhibited optimal growth, food utilization, and survival when fed to satiation once every two days, which corresponds to their 36-hour food deprivation period (Thia-Eng and Seng-Keh, 1978). These studies indicate that the optimal feeding frequency varies among fish species and is influenced by factors such as metabolism, digestive rate, and environmental conditions. To optimize the feed's daily ration, a growth model was developed based on data from Mexican tilapia farms by Domínguez-May et al. (2024). In their model equations, the researchers employed all of the available variables. Therefore, it is crucial to determine species-specific feeding regimens to maximize growth and efficiency in aquaculture. Nowadays the biggest fish feed manufacturing firms generally can supply producers with these regimes, at least in the case of the most important species reared in intensive systems.

The special features of semi-intensive systems

Semi-intensive aquaculture systems account for about 70% of tropic fish and crustacean production (Tacon, 1996). Large pond areas in Central and Eastern Europe also produce in this system, using a range of feeding methods, from low-cost pond fertilization to supplemental feeding of energy-providing cereals, or even high-cost complete diets. However, all forms emphasize the importance of natural food organisms as protein sources. The other cornerstone is polyculture, based on the synergy of species with different feeding habits, a practice derived from traditional Chinese aquaculture (Edwards, 2009).

To gain a deeper understanding of the functioning of a polyculture fish pond from a production biology perspective, it is first necessary to recall the Elton pyramid (Figure 2.), which is a well-known model in this field. The primary producers in a water body are the phytoplankton and higher plants. The decomposers are the bacterioplankton and bacteria as well as invertebrates that dwell in the sediment. The primary consumers are the zooplankton taxa, with the second level comprising mostly omnivorous fish, which serve as food for the carnivores at the highest levels. The red percentage indicates the ratio of energy or weight at a given trophic level. In the case of a semi-intensive fish pond, the feed is a significant input of energy, incorporated in the nutrients, of course.

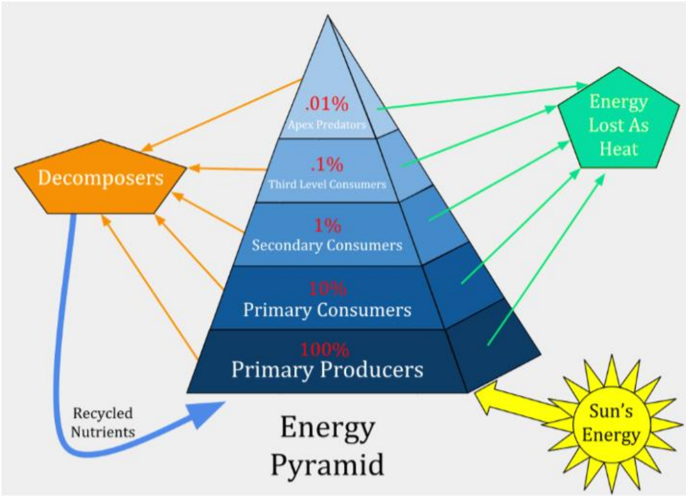

Figure 2. Elton's pyramid on energy relations of ecosystems (Source: Wikipedia)

In the context of the practice of feeding, the factors related to fish are species, variety, sex, and especially age. This is because the efficiency of digestion improves with age. The most significant environmental factor is water temperature. (An increase of 10°C results in a doubling of the metabolic rate.) However, the impact of atmospheric pressure must also be considered. It is of the utmost importance to determine the daily ration, as feeding is typically allowed ad libitum, which makes it easy to commit feed waste. As it is not feasible to directly observe consumption, the only viable approach is to assess the quantity of unconsumed grains at designated feeding locations after a few hours and then modify the daily ration accordingly on the subsequent day. Although feeding once a day is not the most optimal practice, it is common due to the significant costs associated with labour. In the case of female breeders in the period preceding artificial propagation, a restricted feeding regimen is employed. The production of natural feeds is promoted by the use of organic or inorganic fertilizers. In a well-designed polyculture, all trophic levels are exploited by fish. Green fodder is consumed by grass carp, *(Ctenopharyngodon idella)* and the unconsumed part, in addition to the fish faeces, serves as fertilizer. It should be noted that grains are not the only substance that can be used for feeding; many kinds of by-products from the milling and food industries can also be employed, thus contributing to an environmentally friendly, circular economy (Hancz and Horváth, 2007).

Last but not least socio-economic concerns of low and medium-intensity aquaculture need also be mentioned, general aspects and methods of evaluation of which are discussed by Bhari and Visvanathan (2018). Aquaculture has been recognized as a potential tool for poverty reduction and food security enhancement, particularly in low-income countries (Viswanathan and Genio, 2001). While intensive aquaculture has raised environmental concerns, semi-intensive systems are being explored as a more sustainable alternative (Pomeroy et al., 2014). Studies in the Philippines have shown that aquaculture provides new opportunities for poor households, women, and youth, despite challenges such as limited access to credit and skills (Philminaq et al., 2007). The socioeconomic impacts of aquaculture are complex, affecting factors such as employment, food security, and overall well-being. To maximize benefits and minimize negative impacts, integrated farming systems, stakeholder involvement, and well-defined rights are recommended (Pomeroy et al., 2014).

CURRENT ACHIEVEMENTS OF THE AQUATIC ANIMAL NUTRITION AND FEED INDUSTRY

Alternative nutrient sources

In response to the mounting costs and environmental concerns associated with global fisheries, the aquaculture industry has undergone a significant transition, moving away from its historical reliance on fishmeal (FM) and fish oil (FO) as feed ingredients and towards more sustainable alternatives. McLean (2023) provides an overview of animal, microbial, and plant-based feedstuffs that have been examined as potential substitutes for FM/FO. In this regard, plant-based feedstuffs and rendered meat products have been the subject of the most extensive research, and a substantial body of literature exists on their use in the feeding of a wide range of important species cultivated globally. This research is ongoing and is yielding valuable insights. However, alternative sources of nutrients, including single-celled products such as fungi and yeasts, bacteria, and microalgae, are also being investigated as potential sources of protein, lipids, pigments, and enzymes. The role of feed additives, including exogenous enzymes (such as phytases, lipases, proteases, and carbohydrates), is also being evaluated as a means of potentially enhancing the nutritional profile of aquafeeds.

Additionally, chemoattractants and palatants, as well as pre-, pro-, and synbiotics, are being explored as potential tools for improving the digestibility and palatability of aquafeeds. However, due to the limitations of this review, our focus is limited to the latter issues.

Soybean

The use of soybean meal (SBM) and soy protein concentrate (SPC) as alternatives to fishmeal in aquafeeds is becoming increasingly prevalent due to the growing demand and limited supply of fishmeal (Dersjant-Li, 2002; Gatlin, 2003). SBM is a highly nutritious plant protein source, often constituting 50-60% of the diet of omnivorous freshwater fish species (Gatlin, 2003). However, SBM contains anti-nutritional factors that can restrict its inclusion levels (Dersjant-Li, 2002). SPC, which contains reduced anti-nutritional components, has demonstrated potential for partial or complete replacement of fishmeal without adverse effects on growth performance in a range of aquatic species (Dersjant-Li, 2002; Gyan et al., 2019). In recent years, there has been a growing interest and adoption of enzymatically hydrolyzed soybean as a fishmeal substitute in aquafeeds. Huang et al. (2024) demonstrated that replacing up to 45% of dietary fishmeal with enzymatically hydrolyzed soybeans did not negatively impact the growth performance of juvenile Chinese mitten crabs (*Eriocheir sinensis*). Similarly, Tibaldi et al. (2006) demonstrated that substituting 50% of dietary fishmeal with enzymatically hydrolyzed soybean meal has no adverse effects on the growth performance and whole-body composition of European sea bass (*Dicentrarchus labrax*). Furthermore, the use of a multi-enzyme strategy for the hydrolysis of soybean has been demonstrated to be more effective than a single-enzyme approach in terms of substituting fishmeal in aquafeeds. It has been demonstrated that protease-treated soybean meal can substitute for 20% of fishmeal in the diets of largemouth bass (*Micropterus salmoides*). Furthermore, combination treatment with protease and non-starch polysaccharide enzymes has been shown to facilitate the replacement of up to 47.27% of dietary fishmeal with soybean meal for largemouth bass (Zhang et al., 2019). Therefore, soybean protein hydrolyzed through multiple enzymes represents an efficacious substitute for fishmeal in aquafeeds. Xu et al. (2024) obtained similar results on juvenile American eel (*Anguilla rostrata*).

The utilization of organic acids in the domain of aquaculture and the aquafeed industry has recently witnessed a surge in interest. Farmers are keen to enhance their yields through the culture-based system and the commercialization of organic acids in aquaculture, to improve growth performance and disease control. As evidenced by the research reviewed, numerous studies have demonstrated that organic acids, their salts, or blends in feed enhance growth, feed utilization, gut health, and disease resistance in aquatic animals. In general, studies on organic acids have indicated that they can enhance growth performance and nutrient utilization in aquaculture. The growth factor appears to be contingent upon the specific type of organic acid employed and the host organism in question (Ng and Koh, 2011). The utilization of organic acids in aquaculture is gaining considerable traction. The results of research studies indicate that organic acids, their salts, or mixtures can enhance growth, feed utilization, gut flora health, and disease resistance in aquatic animals. However, the beneficial effects vary by species and type of acid, and research suggests that further investigation is needed to understand the mechanisms involved. The economic feasibility of incorporating organic acids is limited, so scientific evidence is needed to support the benefits of their use ("Organic acids in aquafeeds – A sustainable alternative to antibiotics" 2019).

Microorganisms: microalgae, yeasts, fungi, and bacteria

Microalgae, in particular, have high biomass productivity and a low environmental footprint, making them an environmentally sustainable option (Nagappan et al., 2021). However, challenges remain in commercial production, including high costs and the need for novel processing technologies to improve digestibility and reduce antinutritional factors (Sarker, 2023; Siddik et al., 2023). Despite these hurdles, ongoing research and technological innovations are focused on optimizing microbial-derived nutrients for aquaculture, with the potential to significantly contribute to the industry's sustainable growth (Gamboa-Delgado and Márquez-Reyes, 2018; Nagappan et al., 2021).

Sarker et al. (2023) gave an excellent overview of the benefits of using microorganisms in aquafeeds, mentioning first the microalgae protein and oil that has gained momentum for their use in aquaculture feeds. Marine microalgae, particularly have great potential to replace fishmeal and fish oil in salmonids and other finfish feeds because of their high levels of fatty acid and protein content. Marine microalgae, *Nannochloropsis oculata, Isochrysis sp*., and *Schizochytrium sp.* showed promise in aquafeed because they are rich in EPA, DHA, protein, key amino acids (methionine and lysine), lipids, and are good sources of minerals. Defatted *N. oculata* coproducts (leftover biomass oil extraction) contain approximately 20% to 45% crude protein, with good amino acid profiles. Including defatted *N. oculata* as a protein source into diets up to 33% for tilapia and up to 10% for Atlantic salmon did not affect their performance or health status. Another unique benefit of the defatted microalgae is their function in serving not only as an excellent protein source but also as a source of polyunsaturated fatty acids (PUFAs) to enrich n-3 fatty acids. Defatted *N. oculata* is more nutrient-dense compared to the whole cells. The digestibility of lysine (often deficient in terrestrial crop protein) was higher], and the EPA was also highly digestible, making it a good candidate for EPA supplementation in tilapia feed (Sarker et al., 2018) A recent study showed that *Isochrysis* *sp*. is a highly digestible protein, amino acid, lipid, and fatty acids source for rainbow trout. This species could be a good candidate for fishmeal and fish oil replacement in rainbow trout diets and can be used as a health-promoting omega-3, DHA supplement in diets. Research showed that lipids extracted from *Desmodesmus sp*. could be used (20%) in the salmon feeds without any negative effect on growth and fillet composition. A *Spirulina* algal meal could be also incorporated in 10% of the rainbow trout feed without any adverse effect on fish performance (Kiron et al., 2016, Sirakov et al., (2012).

Yeast has also emerged as a viable substitute protein source in the aquaculture industry due to its potential as a nutritional supplement, as illustrated in Table 1. Furthermore, yeast has the potential to act as an effective immune-stimulating agent, thus helping to prevent disease. However, except methionine, lysine, arginine, and phenylalanine, which are typically the limiting essential amino acids in various fish species, the various yeast species have amino acid profiles that are advantageous compared to fishmeal (Sultana et al., 2024).

Table 1.
Chemical composition of *Saccharomyces cerevisiae* yeast meal and fishmeal.

Composition	***Saccharomyces cerevisiae* from beer fermentation**	**Menhaden fishmeal**
Dry matter%	93	91.2–92
ME (kcal/kg)	1990	3370
Crude protein%	44.4	59–68.5
Crude fat%	1	9.1–10.4
Crude fiber%	2.7	0.9
Ca%	0.12	4.87–5.34
P%	1.4	2.93–3.05

Source: *Hicks* et al., 2016; *Bertolo* et al., 2019.

Research indicates that yeast antimicrobial peptides can replace up to 40% of fishmeal in fish diets, with a 1% supplementation significantly improving disease resistance (Gyan et al., 2019). The utilization of yeast in aquafeeds could potentially reduce global fishmeal usage by 13.94% and decrease the carbon footprint of aquaculture, contributing to improved sustainability in the industry. FM replacement using brewer's spent yeast (BSY) is 30–50% for carnivores and 35–80.8% for omnivore fish. Also, the utilization of BSY in the global aquafeed industry could reduce fishmeal usage by up to 13.94% (0.369 MMT) globally and reduce the carbon footprint by about 1.79 megatonnes of CO_2 and fish-in-fish-out ratio (FIFO) from 0.82:1 to 0.71:1. Thus, utilization of

BSY in the aquaculture sector improves circular bio-economy and environmental sustainability in fish production. (Gokulakrishnan et al., 2022).

Edible insects

The production of edible insects for animal feed has seen significant growth over the past decade, due to several key factors, as:

- The increasing global demand for animal protein, driven by population growth and changing dietary preferences, has created a need for alternative protein sources, further stimulating the expansion of the insect farming industry.
- Sustainability concerns include the reduction of greenhouse gas emissions, the conservation of land and water resources, and the optimization of feed conversion ratios.
- The nutritional value of insects is a rich source of protein, essential amino acids, vitamins, and minerals, rendering them an attractive alternative to conventional protein sources such as soy and fishmeal in animal feed.
- Research and development: The increased research into the benefits of insect-based feed has contributed to a greater awareness and acceptance of this practice among farmers and consumers.
- Technological advancements: Technological advancements have led to improvements in farming and processing technologies, thereby enhancing the viability of insect production.

In their introduction to "Insects as Sustainable Food Ingredients," Dunkel and Payne (2016) provide a comprehensive overview of the global significance of edible insects. They highlight the growing demand for animal-based protein, the efficient use of land and water, and the limitations of non-renewable energy sources. In light of the mounting concerns surrounding sustainability, Guiné et al. (2021) present significant findings regarding the efficiency of insects in comparison to other livestock. Furthermore, they indicate that the environmental impact of insect production considers factors such as feed conversion, land use, and water consumption. In comparison to other land animals, insects require the least amount of feed, land, and water. This is followed by chickens, pigs, and cows. In his book chapter, Riddick et al. (2014) provided a comprehensive overview of the utilization of insects as a protein source in aquaculture at the time. This review of the research discusses four key species—the black soldier fly, the common house fly, the silkworm moth, and the yellow mealworm—which were selected as model insects to illustrate the progress been made. It is crucial to consider the variations in protein and fat content across these species, given that they differ not only between species but also between developmental stages within a species. The primary findings of the study indicated that the inclusion of insects in the form of meals or pellets could provide an adequate protein source to partially substitute for conventional fish meals in the diets of omnivorous fish species, such as catfish and carp, as opposed to carnivorous fish, including trout and salmon. It is imperative to develop cost-effective, large-scale farming techniques to meet the increasing demand for farmed fish.

Additionally, it is important to consider that insects serve not only as meal replacements but also as probiotics due to their chitin and AMP content. The inclusion of insect meal in fish diets, even at relatively low levels, has the potential to enhance the immune system of fish and improve their performance, as evidenced by previous studies in other livestock species. It is also important to note that there are more than 200 species of farmed fish, and their dietary requirements remain poorly understood. Furthermore, the process of insect meal elaboration before its incorporation into animal feed warrants consideration (Nogales Mérida et al., 2018). In their 2022 overview, Hameed et al. discussed the potential benefits and opportunities of insect-based feed, emphasizing its capacity to enhance the sustainability and efficiency of aquaculture practices. The authors of the review article in question cite recent research and studies on the use of insects as a feed source for fish and other aquatic species.

Feed additives

Modern aquafeeds generally contain the following basic ingredients:

- Fishmeal: A primary source of protein derived from fish, providing essential amino acids and omega-3 fatty acids.
- Soybean meal: A common plant-based protein source, often used to supplement fish meal.
- Corn gluten meal: Another plant-based protein source, adding both protein and energy.
- Wheat gluten: Provides protein and helps improve the binding and texture of the feed.
- Fish oil: A source of essential fatty acids, particularly omega-3, important for growth and health.

Using the following kinds feed additives in different concentrations depends on factors like species, age group, heath status and production goals and keeping conditions.

- Vitamins: Essential vitamins such as A, D, E, K, and B vitamins to support overall health and growth.
- Minerals: Essential minerals like calcium, phosphorus, magnesium, and trace minerals such as zinc, copper, and selenium.
- Binders: Ingredients like wheat bran or starch are used to improve pellet stability and texture.
- Probiotics and prebiotics: To enhance gut health and improve nutrient absorption.
- Antioxidants: Such as tocopherols or ascorbic acid to maintain feed quality and stability.
- Flavoring agents: To enhance palatability and stimulate feeding.
- Coloring agents: To improve the appearance of the feed or the coloration of the fish.

The specific composition of the ingredients may vary depending on the particular nutritional requirements of the aquaculture species in question, and may also be adapted to reflect local availability and cost-effectiveness.

A feed premix is defined as a concentrated blend of vitamins, minerals, amino acids, and other nutrients that have been formulated for addition to animal feed. The objective is to guarantee that the ultimate feed mixture provides the essential dietary requirements for any livestock in general, and also for aquaculture species, of course3. The use of a premix allows producers to efficiently balance the nutritional content of the feed, thereby enhancing animal health, growth, and productivity. Feed premixes can be formulated to meet the specific nutritional requirements of a given species or production goal. They are typically mixed with a base feed ingredient before administration to animals. A premix is defined as a blend of micro-ingredients mixed into a carrier substance. The addition of a premix to a feed is often the smallest, yet has the potential to have the most significant impact on the nutritional value of the feed. An effective premix should facilitate the uniform distribution of micro-ingredients and enhance their absorption. The selection of an appropriate carrier for the micro-ingredients can facilitate the attainment of optimal characteristics concerning flowability and homogeneity. Furthermore, the utilization of suitable and stable forms of vitamins and minerals is crucial to guarantee optimal bioavailability for the intended species. Furthermore, innovative oral delivery systems, including bio-encapsulation and enteric-coated beads, are being developed to enhance the efficacy of in-feed medications (Daniel, 2009). The objective of these advancements in aquafeed premixes is to facilitate sustainable growth in aquaculture while addressing challenges related to fish health and environmental concerns.

Modern aquafeed premixes have undergone significant developments to address concerns related to sustainability and to enhance the health of fish. While fishmeal and oil were historically the primary ingredients, their limited supply has prompted the investigation of alternative sources (Hardy, 2009). Microalgae biomass is emerging as a promising sustainable feed ingredient, offering essential nutrients and bioactive compounds that can enhance fish survival, colouration, and fillet quality (Nagappan et al., 2021). Probiotics, prebiotics, and synbiotics are increasingly incorporated into aquafeeds to improve growth performance, immune competence, and overall fish well-being (Rohani et al., 2021). These bio-friendly additives can potentially mitigate stress and enhance the composition of the intestinal microbiota. The extensive research conducted on prebiotics and probiotics has resulted in the rapid production and broad-scale application of these bioactive compounds in various fields, including medicine, nutrition, and agriculture. However, the intensification of aquaculture practices has increased the stress for aquatic animals and the environment. Various chemicals and antibiotics have been applied that cause serious problems and indirectly affect human health and even directly by producing antibiotic-resistant bacteria strains. Nevertheless, novel products and applications may significantly alter the profile of good practices in many fields, from disease prevention to water quality management, and usher in a new era of sustainable development in this field (Hancz, 2022).

The use of phytochemicals (also called phytoactive or phytobiotics) is also flourishing in aquaculture. These are alkaloids, flavonoids, pigments, phenolics, terpenoids, steroids, and essential oils of plant-derived compounds associated with maintaining good health in the human cultural heritage of many countries. The phytochemicals contained in herbs can enhance the innate immune system and possess antimicrobial capabilities that can be used without causing environmental and/or hazardous problems. Most phytochemicals are redox-active molecules having antioxidant properties that can improve the overall physiological condition of fish, thus acting as growth promoters. Their endocrine-modulating ability can even be used for sex reversal (Chakraborty and Hancz, 2011; Chakraborty et al., 2014). Tastan and Salem (2021) and Dev et al. (2024) provided comprehensive overviews of the most recent advances in this field, emphasizing the necessity for further studies to investigate the potential synergistic effects of combined phytochemicals. Additionally, they underscored the importance of conducting more extensive research to assess the industrial applications of phytochemicals on a larger scale.

CONCLUSIONS

Sustainability has become a key issue in all areas of human activity concerning the environment, climate, social stability and well-being, and ultimately the future of humanity in a thriving globe. Aquaculture has an important role to play as a supplier of healthy food and as a possible guardian of the good quality and biodiversity of natural waters.

Semi-intensive pond aquaculture has evolved *ab ovo* according to the principles of sustainability and so provides a model for a holistic approach to sustainability.

Feed production and feeding technology are certainly the most important areas of the aquaculture industry, both from an economic and environmental point of view, especially in different types of intensive systems. The production of balanced diets that meet the physiological needs of an ever-increasing number of aquatic animals has already yielded tremendous results and is in constant progress.

In addition to the traditional components of feed additives such as vitamins, minerals, binders and antioxidants, relatively new supplements such as prebiotics, probiotics and phytochemicals are particularly important. The latter can help reduce the use of hazardous chemicals and antibiotics.

Fortunately, all of the above areas of aquatic animal nutrition, which are of immense economic importance, are undergoing intense research and development that will help achieve sustainability goals.

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