Nutritional innovations in aquafeed for sustainable and eco-friendly fish farming

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Abstract

Aquaculture (AC), the most rapidly expanding food business globally, generates more than fifty percent of all fish intended for human consumption. AC feeding comprises fishmeal and oil derived from wild-caught seafood, such as sardines, providing ecological, nutritional stability, and economic benefits. Microalgae, yeasts, fungi, bacteria, and other organisms have potential as constituents in Aquafeeds (AF), supplying proteins/amino acids, lipids, omega-3 reports, and bioactive compounds. This review study examines the deficiencies in research about recent advancements in utilizing microbes, technological innovations, problems, and prospects for creating AC diets with a minimal environmental impact. The components frequently necessitate innovative processing technologies to enhance digestion and fish development while minimizing antinutritional effects. This gap is significant to address, as microalgae are the predominant organisms utilized in fish feed, especially as dietary supplements or combined with other components. The stages of manufacture, processing, and formulation can influence the nutritional attributes. Systematic strategies are necessary to assess these components for feed implementation. In this article, the research delineated the sequential key methodologies for evaluating dietary and ecological reaction metrics to formulate extremely sustainable aquatic farming for AC utilizing these microbes. This would facilitate a more prudent incorporation of these novel components.

Keywords: Fish farming, Nutritional innovations, Aquafeed, Sustainability, Food

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Introduction

Aquaculture (AC) (Vijuksungsith *et al.*, 2023), the most rapidly expanding food business worldwide, currently generates almost fifty percent of all fish for consumption by people, as global catch fisheries have attained or surpassed their sustainable thresholds, stabilizing at around 92 million tons per year (Chaname-Chira *et al.*, 2024). AC is the most significant protein producer globally and will be essential in addressing the considerable problem of feeding over 8 billion individuals by 2060, fulfilling the increasing demands for water, energy, and food while preserving the environment and safeguarding livelihoods (Teoh *et al.*, 2023). The need for fish has significantly propelled the remarkable growth of worldwide AC. The need for fish and seafood has consistently risen, with AC progressively satisfying the need for human consumption, rendering it essential for the future food supply (Tran *et al.*, 2023). AC is anticipated to sustain its significant growth, with projections indicating the production of 110 million kilograms of fish by 2035 for worldwide consumption (Ergüden *et al.*, 2022). Federal AC experienced an increase of 168% from 2010 to 2025, reaching approximately 70 million metric tons of productivity. Manufacturing AC supplies for feed farming is anticipated to rise, with projections indicating the usage of 74.6 million metric tons of feeds by 2030.

The environmental consequences and rising feed costs for AC (Aquafeeds (AF) (Ghamkhar and Hicks, 2021)) hinder the advancement of farming. Feeding has the most major ecological effect throughout the supply chain of the intensively fed AC sector, as yields rely on providing animals with nutritionally sufficient formulated meals (Malešević, Z *et al.*, 2023) Due to its swift proliferation, the ecologically sound operation of farmed food production methods is a significant challenge.

AF was recognized as a significant contributor to adverse environmental consequences, with the manufacture of feed components being the primary source of global warming potential and other pollutants. Feed components' manufacturing and supply chain significantly contribute to the Greenhouse Gas (GHG) emissions (White and Gleason, 2023) associated with AC. The utilization of terrestrial crops and the corresponding land-use alterations, the capture of indigenous fish (e.g., anchovy, sardines, etc.) for fish meal and fish oil, together with the related manufacturing and shipping, frequently contribute to emissions of GHG in AC. AC, the most rapidly expanding agricultural sector, necessitates immediate attention to the significant GHG emissions linked to AF production, manufacturing, and the intricate distribution system. GHG emissions in AC can be mitigated by modifying feed composition and minimizing eutrophication (Singh et al., 2023).

GHG emissions are associated with the Feed Conversion Ratio (FCR) (Callegaro *et al.,* 2022), which denotes the quantity of feed necessary to produce one kilogram of fish (Xue, 2024). Enhancements in the FCR can be realized by innovations in feed composition that reduce the FCR. High-performing new components and the cultivation of algae feed can enhance the Protein Efficiency Ratio (PER) (Sarker, 2023), digestion, feed waste impact on the natural world, and GHG emissions.

AF ingredients constitute 45-70% of the overall expenses and 70-80% of the fluctuating costs in the AC sector, serving as critical market determinants for the industry. The AF industry is expanding, projected to increase by 8-12% annually, reaching $195 million by 2025. The output of industrial AC feeding is anticipated to rise, with an estimated 75.4 million metric tons of blended feed forecast for utilization by 2030. In 2019, around 52.5 million metric tons were generated.

AC and AF Manufacturing

In the last forty years, AC manufacturing has surged with the development of AFs (Park and Kim, 2021). The aqua-feed sector commenced in the 1985s and has since experienced considerable growth. In 1992, AF production was merely 760k tons, escalating to 25 million tons by 2022, representing a thirtyfold growth over three decades (Figure 1). However, a significant discrepancy remains between total AF generation and overall AC output. Although certain farming types, such as rice-fish co-culture and filter-feeding AC, do not depend significantly on formulated feeds, substantial potential exists for the advancement of AFs. The spatial distribution of farming and aqua feed production varies by region (Clawson *et al.*, 2022). The total amount of farming and AF in the eastern and southern regions significantly exceeded that of the northern and western areas. The leading five regions in fish production are Guangdong, Shandong, Fujian, Hubei, and Jiangsu, with yearly outputs of 8.2, 7.3, 7.8, 5.9, and 5.7 million tons, respectively. These provinces together account for more than fifty percent of the national production.

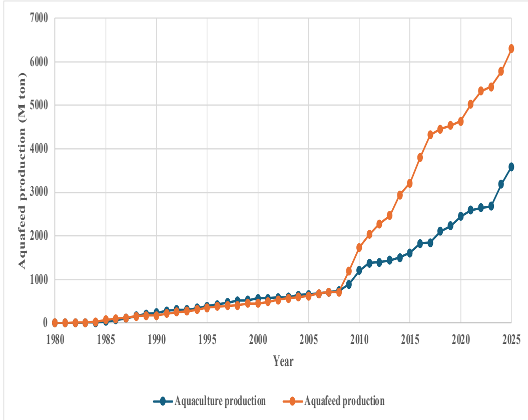

Figure 1: AF production analysis.

The trend in the geographical distribution of aqua-feed output mirrors that of AC. These regions account for over 72% of the national AF output. The elevated AF manufacturing in these places is due to AC's comparatively high production levels, resulting in increased demand for aqua feed. As human living conditions have improved, the quality and safety of aquatic goods have garnered increased attention. AC studies on nutrition have concurrently shifted their emphasis towards conserving resources and environmentally friendly methods.

- *Safety and Well-being of Aquatic Livestock Products*

The utilization of antibiotics has generated apprehensions regarding their resistance and the existence of drug residues in animal tissues, hence endangering human health (Muteeb *et al.*, 2023). About fifty percent of the productivity loss in AC is attributable to disease. Fish epidemics, leading to considerable financial losses, are frequently associated with contamination of the environment and nutrient deficiencies that compromise the immune systems of aquatic organisms. Through the examination of explicit processes, both nutritional and non-nutritional regulatory measures have been established to bolster the defenses of cultivated aquatic organisms, enhance their health, elevate survival rates, diminish pharmaceutical usage, and guarantee the safety and efficacy of aquatic goods. Toll-like receptors were identified as recognizing dsRNA in the cell membranes, initiating inflammation in monocytes of the giant yellow croaker via the nuclear factor kappa B and type I interferon systems.

- *Quality of Aquatic Products*

The quality of fish flesh comprises a complex array of properties influenced by internal and external causes. Multiple studies have shown that flesh quality is intricately linked to nutrition, and inadequate nutrients or components can substantially decline AC fish’s flesh texture and flavor. It is essential to examine the processes through which nutrition influences the quality of aquatic goods, and based on this understanding, to develop additions that enhance their quality.

Numerous recent studies indicate disparities in the capacity of ocean and freshwater fish to produce extremely unsaturated fats. Omega-3 fatty acids, including Eicosapentaenoic Acid (EPA), are recognized for their advantageous impact on wellness and disease prevention. The elongase of rainbow trout has greater access to chromatin and promoter activity than the giant yellow croaker, potentially elucidating the marine fish's superior ability to synthesize EPA. Prior research has indicated that the systems regulate fish muscles' nutritional content and flavor. These mechanical insights provide significant references for designing useful fertilizers and harnessing nutrients to improve the quality of aquatic goods

- *Conservation of Resources*

AC has become the predominant user of worldwide fishmeal, representing 68% of yearly output. Fishmeal is extensively utilized as a source of protein from animals in aqua feed owing to its suitable taste and substantial nutritional content. The limited availability of fish meal as a high-quality protein source has increased prices, prompting the exploration of alternate protein sources. Recent investigations globally have concentrated on identifying suitable alternatives to fishmeal. The research searched the Web of Science archive utilizing the terms 'fishmeal substitute' and 'AC'. The study identified 820 publications published in the past ten years, of which 24.2% originated from research organizations. Research on replacing fish meal with plant-based protein components has garnered significant interest. Numerous plant-derived components, including soy and cottonseed meals, are being utilized as substitutes for seafood meals in AF owing to their low market cost and ethical manufacturing practices. Using ingredients from plants presents numerous constraints, including anti-nutritional elements, significant dependence on arable land, fertilizers, and water, and rivalry for food resources with people.

- *Sustainable*

Safeguarding the aquatic ecosystem and guaranteeing the future viability of AC is a significant objective for the AC sector. Marine animals were fed wild fish or inferior manufactured diets, resulting in increased phosphorus and nitrogen output and subsequent degradation of aquatic ecosystems. In a substantial, high-density AC sector, the surplus of residual bait and excreta surpasses the breakdown capacity of microbes, leading to elevated nitrogen and phosphorus levels in the water, degradation of the water's cleanliness, and Eutrophication. This finally leads to the AC ecosystem's dysregulation of substance and energy cycles.

In recent years, there has been a transition towards improving feed formulas to enhance nutrient use and minimize excessive nutrient and phosphorus output. A prior study indicated that including exogenous digestive enzymes, such as phytase and non-starch polysaccharides digestive enzymes, in meals decreased nitrogen and phosphorus output in seabass. Diets supplemented with phytase enhanced mineral consumption and decreased phosphorus output in the fish. Diets containing 1500 U/kg phytase improve growth and reduce the amount of phosphorus and nitrogen excretion in Channel zebrafish.

Essential Approaches for Assessing Nutritional and Ecological Sustainability

Digestibility of Substances

The digestibility of AF components is crucial for creating economically feasible and environmentally sustainable feeds; publicly accessible digestion data are scarce for alternative components. This deficiency of knowledge frequently compels AF producers to infer the nutritional value of items based on their chemical makeup. Due to the inadequacy of fundamental biochemical analyses and the insufficient amount of amino acids and amino acids in components to guarantee the requisite levels of digestible proteins and amino acids for specific fish species, it is essential to perform digestibility tests. These experiments ascertain the digestibility of components and facilitate diet formulation based on absorbed nutrients, thereby minimizing feed costs, mitigating contaminants (which include fertilizer and phosphorus eutrophication GHG), and enhancing the conversion rate of aqua feeds.

The primary cause of the enhanced FCR attained nowadays is the substantial increase in digestible calories and nutritional density of the meals. The AF manufacturing will benefit from utilizing other substances in feed mixes if they possess particular details regarding the nutrient and antinutrient structure, such as pectin, lectin, chitin, protease inhibitors, oxalate, and tanning.

FCR

Formulating sustainable feeding with other components should be guided by feed efficacy with a reduced FCR. The FCR is a standard effectiveness metric, determined by the ratio of consumed feed to weight increase. It indicates the ecological viability of AC by measuring phosphorus and nitrogen waste emissions in aquatic environments, which lead to adverse effects such as eutrophication, GHG emission levels, diminished biodiversity, and the degradation of additional ecosystem services. The role of AC in GHG emissions is closely linked to the FCR and the source of the feed ingredients. AC's FCRs have decreased from approximately 4 to about 2.4 during the past several decades. This is primarily due to advancements in feed products, methods of production, and on-farm feed management techniques. Salmonid farming enhanced the FCR from roughly 2-2.5 to around 0.8-1.4 since 1980, attributed to enhanced feed composition with highly digestible components, technical advancements, and effective on-site feed administration. Developing environmentally friendly feed compositions for other kinds of fish, including carps, catfish, tilapia, and marine lobsters, is imperative. The feed efficiency ratio indicates that fish are the least efficient species among all intensively farmed animals. For instance, farmed fish can transform roughly 1.7 kg of dry feed into 1 kilogram of wet flesh; the feed conversion ratios for chicken, pig, and beef are 1.6, 3.8, and 6.7, respectively.

Life Cycle Analysis (LCA) for Evaluating Environmental Impact

The environmental effects of AF can be assessed using an LCA, a crucial instrument for evaluating the ecological implications of food sources. The formulation of environmentally friendly feed utilizing alternative components must consider areas of environmental impact, such as resource utilization, release of GHG, eutrophication, biodiversity decline, and adverse externalities like acidifying the oceans. Data on the life cycle environmental consequences and emissions of new substances is exceedingly scarce. The environmental impact categories, established by an LCA, must be incorporated into the procedures for assessing novel ingredients. No contemporary food production system regarding energy consumption and biodiversity depletion is genuinely efficient. This data is crucial for determining the efficacy of novel compounds and juxtaposing them with synthesis. The green AF sector is nascent, and the comprehensive environmental impacts of generating innovative ingredients remain unquantified.

A comprehensive perspective on sustainability is thus required. The mass production of novel components relies on fossil fuels, and developing high-quality alternative proteins and oils necessitates understanding the life-cycle impacts of these component alternatives in diets. Further research on the LCA of presently accessible unorthodox feedstuffs is essential to enhance the understanding of future environmentally conscious agribusiness components.

Innovative Technology for Enhancing Ingredient Quality

Enhancing overall feed efficiency, feed conversion proportion, and accessibility of protein components will assist the AF sector in satisfying the global demand for these scarce resources. Numerous factors contribute to the improvement of feed effectiveness and the formulation of cost-effective diets: (i) the nutritional value of protein components, encompassing the amount of protein, amino acid description, and antinutritional factors; (ii) the capacity to fulfill protein and necessary amino acid needs of a specific type of fish at various life stages, as the ontogenetic developmental stage of the fish can markedly influence the dietary protein or vital amino acids that are needed; and (iii) the fish's capacity to break down and absorb the consumed nourish protein. Innovative technologies have emerged to enhance the effectiveness of the feed conversion ratio, digestion, and protein effectiveness of components. Microalgae are now in the nascent phase of incorporation into AC eating habits, and further preparation of these nutrients improves energy and protein digestion. The digestion of nutrients in microalgae components is challenging due to their cell walls' stiffness. Cell walls can be disrupted through various methods to enhance the digestion of tiny algae: enzymes, chemicals, and physical processes.

Physical digestion effectively partially or wholly inactivates antinutritional substances. Physical and chemical approaches are typically used, while enzyme and chemical approaches affect intracellular nutrition. Heating or frying can inactivate enzyme inhibitors and lectins in soybeans. A recent study indicated that intact Chlorella colonies and burst cells possessed identical nutrient contents; the ruptured colonies exhibited enhanced digestibility for essential nutrients such as amino acids, lipids, and carbs compared to whole Chlorella cells.

Extrusion Machining

The unique extrusion process provides the benefit of utilizing a broader range of materials. Twin screw extrusion technique can process, settle down, and integrate materials. The extruder possesses many capacities, including drying, crushing, and other associated apparatus for executing pilot-scale production operations. Extrusion processing subjects components to elevated conditions and pressures for a brief duration, facilitating preparing food and pasteurization, thereby eradicating antinutrients and enhancing feed consumption, nutrient digestion, and the development efficiency of fish. Extruded feed permits the incorporation of elevated fat levels in diets, whereas gelatinization from starch enhances the absorption of energy and proteins in meals. Extrusion enhances the durability of feed, reduces particles, and allows for variation in the physical properties of the pellet, such as buoyant or sinking behavior.

Application of Exogenous Bacteria in AF

Protease proteins enhance natural peptidases by augmenting protein digestibility and hydrating proteinaceous anti-nutrients. High-quality amino acids or cocktails can be formulated for specific amino acids, such as keratin-rich poultry wings, according to digestion circumstances, including stomach or intestine pH, thereby improving protein intake breakdown and utilisation. A monogastric species, including rainbow trout, exhibits negligible nonstarch polysaccharides enzyme production in its digestive system. Applying catalysts to components improves the digestion and use of alternative foods. The addition of such digestive enzymes has demonstrated enhanced nutrient digestion, improved consumption of nutrients, higher development of fish, diminished nutrient waste, and reduced antinutritional factors in grounded plant materials for fish, especially the rainbow trout.

Utilization of Additives in Aqua Feed to Enhance Palatability

Incorporating taurine with other ingredients might augment the taste of reduced fish meal or fish-free diets and boost digestion and lipid absorption. Amino acids are neutral beta-amino acids obtained from the breakdown of sulfur-rich amino acids in food. Taurine was deemed non-essential for fish; however, recent studies have demonstrated its critical significance in AC food, enhancing growth, feed intake, and feed efficiency. Fish-based diets are abundant in taurine; hence, salmonids or other fish that eat meat necessitate exogenous thiamine in fish-free feed to sustain their physiological processes and enhance their feed consumption. Using choline in AF with reduced fish meal content has enhanced feed intake and development rates for fish such as trout, sardines, and fluke.

Obstacles and Prospects in the Adoption of New AFs

The average proportion of soy and corn in fish meals is 40-60%. Substituting agricultural products with existing fish feed alternatives will be prohibitively expensive for widespread implementation by AF makers and farmed companies. The AF business will utilize other components if they are cost-competitive with soya and maize and maintain a consistent supply amount. Academics and AC sector stakeholders must engage in joint efforts and undertake a systematic study to establish an optimal, efficient, and lucrative alternative while mitigating adverse social, ecological, and economic effects. To achieve this objective, researchers must conduct incremental studies to identify an environmentally friendly option, whether through a novel component, an amalgamation of elements, or a coproduct or a result that can either entirely or partially substitute crop proteins in aquatic feeds, and to assess how this mixture influences fish development, flesh excellence, and both financial and environmental outcomes.

An assessment of the long-term reliability of novel components is receiving increased focus. Various methodologies have been employed to delineate viability; an LCA is arguably the most effective technique. The laboratory is now creating an open-access decision-support tool incorporating technoeconomic and lifespan analyses and a nutritional evaluation of various alternative components, ranging from insect meals to tiny algae, for fish-free farmed feeds.

It is imperative to recognize that the primary issue lies in achieving stability in the availability of microalgal components for large-scale commercial production. A significant difficulty is the competitive pricing of unusual components compared to traditional ones. The cost will be the primary limitation influencing the future trajectory of the AF sector and business. Scaling up presents a significant obstacle for these innovative compounds.

The primary difficulty is the affordable cost of new components compared to conventional ones. Agricultural feed producers are prepared to offer a comparable price per ton for soybean protein concentrates for fish meal. Conventional fish feed ingredients constitute a substantial portion of aqua feed, whereas the incorporation of novel raw materials remains limited due to inconsistent supply and affordable prices. Scientists and algae must identify methods to reduce the expenses of producing and processing innovative components. The basic materials must be consistent in each batch for accurate feed products. If an insect is cultivated using several waste streams, its nutritional contents will be variable. Innovative components' manufacturing volumes, including microalgae, yeast, bacteria, and insects, remain comparatively small, resulting in a limited market share compared to conventional feed components. While substituting fish oil with algae demonstrates potential, cultivating microalgae and oil extraction necessitates modern technologies, specialized knowledge, and financial resources. Utilizing these innovative elements is not economically viable for small-scale AC manufacturers in developing countries. The current adoption of novel components remains arduous and is unfair for all producers globally. Transitioning from traditional AFs to those utilizing novel components presents numerous regulatory, financial, and ecological challenges, particularly for smaller enterprises and those in developing nations.

Notwithstanding the restrictions above, should the stakeholders concur to use innovative components in AFs whenever practicable, it would significantly alleviate the reliance on wild-caught seafood in AC diets, ensuring the future viability of the fish farming sector. It is necessary to explore financial incentives, investigate marketing prospects, and promote the ecocertification for environmentally friendly products. Consumer tastes and understanding regarding sustainability are increasing, accompanied by a favorable public disposition towards innovative components, as seen by a readiness to pay higher prices for environmentally friendly goods, which can further augment the financial benefits of incorporating novel components.

Conclusion

About advancements in the creation of innovative components, it is essential to assess the nutritional profiles of each component, encompassing nutrient value, taste, feed consumption, and digestion. This necessitates that investigators perform dietary feeding tests in laboratories and conduct consumption and developmental trials on farm animals. Certain substances require further processing to enhance digestion, increase FCR, and mitigate antinutritional effects. The diverse processing methods enhance the potential for generating cost-effective, protein-rich components and minimize total manufacturing expenses. The final phase of the nutritional assessment of alternative components necessitates a thorough economic study to guide judgments regarding incorporating unorthodox products into diets that remain cost-competitive with traditional ingredients. Recent studies indicate the potential to generate yields of innovative components, such as tiny algae, that are many times higher per unit area than terrestrial agricultural products like soy protein, utilizing the same land footprints with carbon dioxide from the atmosphere and solar power. The environmentally friendly manufacturing strategy indicates a new emphasis on conducting life-cycle assessment analyses of novel components. To comprehensively develop environmentally friendly replacement components, researchers must employ systems-based methodologies that amalgamate information and skills from various disciplines, such as fish dietitians and fish farming scientists, to execute on-farm consumption trials in collaboration with producers, ecologists, technoeconomic and LCA extension researchers, and analysts.

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