Colegio de Postgraduados

Diversity of by-products used in fish diets in the aquaculture industry: a systematic review

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ABSTRACT

Objective: The purpose of this systematic review was to identify and analyze studies evaluating the use of agro-industrial by-products as alternative ingredients in farmed fish diets, synthesizing the evidence on their impact on productive and nutritional performance, as well as contextualizing the temporal, geographic, and multidisciplinary trends in this line of research.

Methodology: A systematic search of scientific databases (1999-2024) was conducted using terms related to aquaculture and agro-industrial by-products. Of 1,015 articles identified, 32 met the inclusion criteria, which required experimental studies in farmed fish. Information on species, by-product type, inclusion level, and production parameters was extracted from each study.

Results: The temporal analysis showed sustained growth in the number of publications, with a notable increase starting in 2013, reflecting a growing global interest in sustainable alternatives to fishmeal. Geographically, Nigeria accounted for most of the studies, followed by Egypt, Mexico, and the United States. By-products were classified into six categories: vegetables, terrestrial animals, fish, hydrolyzed meals, bioprocessed meals, and microbial biomass. Ingredients such as brewery waste, poultry meal, and fish silage reported favorable results, with FCR≤1.1 and SGR≥3.5%. Bioprocessed meals and microbial additives showed consistent improvements in digestibility and yield.

Limitations/Implications: Practical application depends on regional availability, the presence of antinutritional factors, processing requirements, and producer acceptance, emphasizing the need for comprehensive assessments that include economic, environmental, and health aspects.

Conclusions: The findings demonstrate that various agro-industrial by-products can partially or totally replace fishmeal without compromising production performance, favoring the economic viability and sustainability of aquaculture.

Keywords: sustainability, aquaculture nutrition, feed conversion, alternative ingredients, digestibility.

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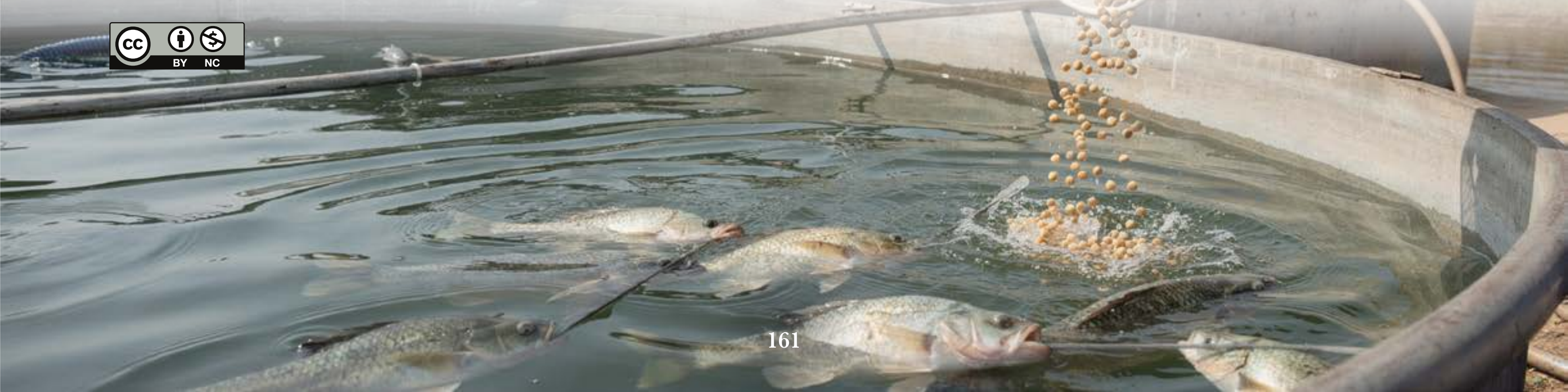

INTRODUCTION

Aquaculture has become a fundamental pillar of global food security, offering a sustainable alternative to the challenges posed by the overexploitation of wild fish stocks and the impacts of climate change [1]. Over the last three decades, it has established itself as the main driver of growth in fisheries and aquaculture production, with an average annual increase of 5.0% between 2000 and 2021. This upward trend is expected to continue in the coming decades, mainly due to advances in nutrition, management, reproduction, and technological innovation in farmed species, all of which contribute to their success and sustainability [2,3]. Nevertheless, aquaculture remains heavily dependent on unsustainable resources. For more than 50 years, the industry has relied on fishmeal (FM), a highly valued ingredient due to its exceptional nutritional profile. FM contains 60-72% highly digestible protein with a complete essential amino acid profile (notably lysine and methionine), 5-12% lipids rich in omega-3 fatty acids (EPA and DHA), 3,000-4,000 kcal/kg of metabolizable energy, and a wide range of vitamins and minerals, including bioavailable phosphorus critical for bone development and energy metabolism [4,5]. Although FM is highly palatable and digestible (85-95%), its use raises sustainability concerns due to reliance on small pelagic fisheries and high production costs [6]. In response, the aquaculture sector has intensified the search for innovative alternatives that ensure nutritional quality while reducing dependence on FM. Agro-industrial by-products have emerged as a promising option, allowing for optimized raw material use and promoting circular economy practices [7]. By-products are defined as whole bodies or parts of plant and/or animal origin derived from food production and processing for human consumption. Their generation is inevitable and difficult to modify without affecting final product quality [8,9]. Globally, more than 1.3 billion tonnes of by-products are produced annually, equivalent to 13.8% of all food production [10]. This enormous volume has profound environmental, economic, and social implications [11]. If not properly managed, it not only increases disposal costs but can also generate aesthetic problems and serious public health risks. In aquaculture, their incorporation into formulated diets has been proposed as a sustainable and cost-effective alternative [8]. Several sources of animal protein have been evaluated, including by-products from the poultry and swine industries, aquaculture processing residues, and agricultural by-products [12,13]. Such approaches contribute to reducing waste, recycling raw materials, and improving the sustainability of feed production. Therefore, the main objective of this study was to conduct a systematic review of the use of agro-industrial by-products as alternative protein sources in diets for farmed fish, to identify the types of by-products used, analyze their effects on production performance, and compare their effectiveness with diets based on fishmeal.

MATERIALS AND METHODS

A systematic review of the scientific literature was conducted using the Scopus and Web of Science databases, covering the period from 1999 to 2024. A combined search string was applied in English and Spanish: ("By-products" OR "Subproductos") AND ("Aquaculture" OR "Acuicultura"). Only original research articles evaluating the use of agro-industrial by-products as ingredients in fish diets were included. Reviews, editorials, book chapters, conference proceedings, duplicate records, and studies assessing alternative ingredients not derived from by-products were excluded. The selection process was carried out in three stages. First, titles, abstracts, and keywords were screened, identifying 491 potentially eligible publications. In the second stage, studies were excluded if the experimental organisms were not fish or if diets contained more than four different by-products. Finally, full-text articles were assessed, and only those reporting at least four of the following five performance parameters were retained: initial weight, final weight, specific growth rate (SGR), feed conversion ratio (FCR), and survival. Reporting of the standard error was required as a criterion for statistical validity.

Data from the selected studies were compiled in an Excel spreadsheet, including type of by-product used as an alternative protein source, fish species evaluated, inclusion level (%), experimental duration (days), feeding frequency (times/day), and production performance outcomes.

RESULTS AND DISCUSSION

A total of 1,015 articles were identified through the selected databases, with no additional records retrieved from other sources. After applying all eligibility criteria, 32 articles were included in the systematic review (Figure 1). Figure 2 presents the distribution of publications across scientific journals. Research on the use of agro-industrial by-products as alternative ingredients in fish diets has been published in a wide variety of specialized journals, reflecting the technical, productive, and multidisciplinary scope of the field. Aquaculture was the leading journal, with four publications, followed by the Journal of the World Aquaculture Society with three. Aquaculture Research, Global Advanced Research Journal of Agricultural Science, and the Journal of Applied Aquaculture each published two studies. The remaining journals contributed a single article, illustrating thematic dispersion from aquaculture-focused outlets to those dedicated to animal science, physiology, or agricultural sciences. The temporal evolution of publications is shown in Figure 3, which depicts both annual (blue) and cumulative (red) outputs between 1999 and 2024. Overall, there was sustained growth in cumulative publications, although the annual output remained relatively low and variable. During the first decade (1999-2009), production was sporadic, with no more than two articles per year and several years without records. From 2013 onwards, publication became more regular, with a modest increase between 2013 and 2015 (up to three studies per year). The most pronounced cumulative growth occurred between 2015 and 2022, when more than 60% of all identified studies were published, suggesting a growing research interest in sustainable aquaculture diets. The year 2020 marked a peak with three publications, followed by stabilization in subsequent years. In 2024, output declined to a single publication, although the cumulative total reached 32 articles. Figure 4 shows the geographical distribution of publications. While there was moderate global dispersion, most studies originated from developing countries with strong aquaculture activity and availability of agro-industrial by-products. Nigeria led with five publications, highlighting the emphasis on local by-products to enhance aquaculture sustainability.

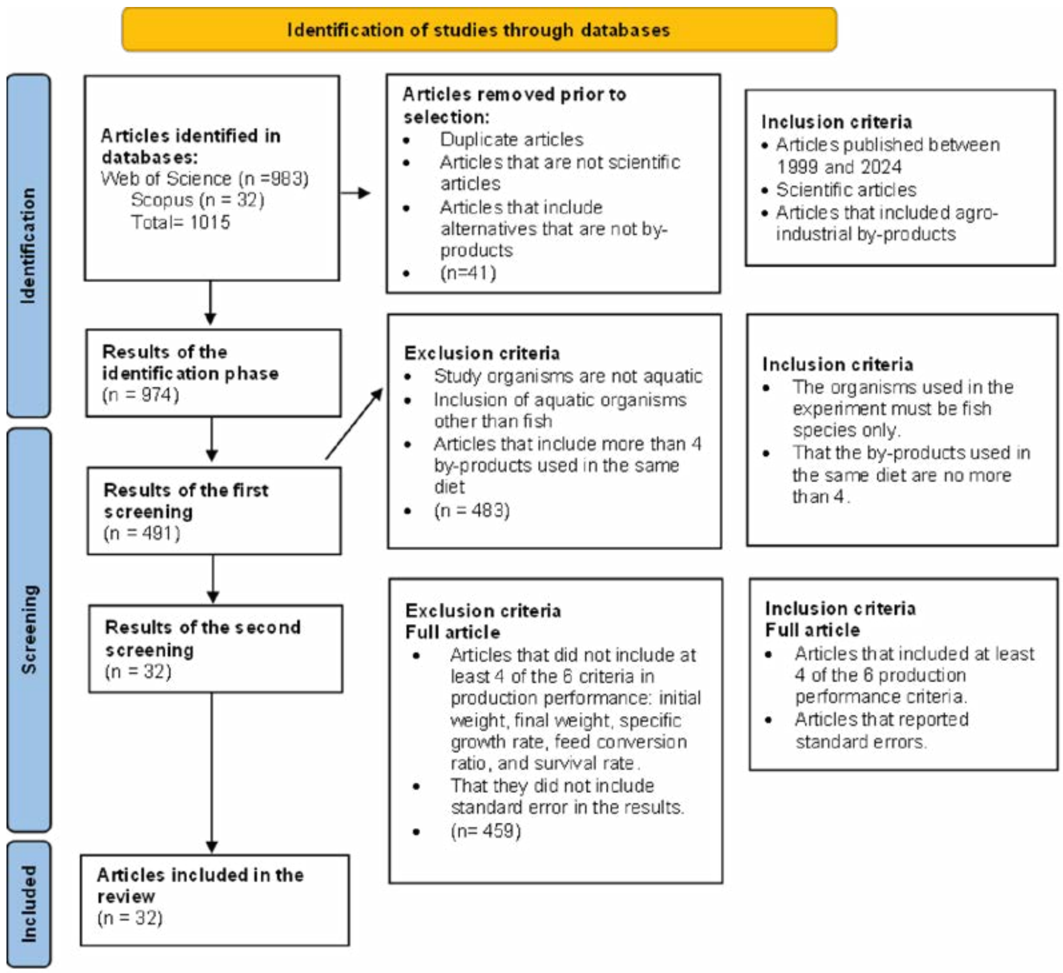

Figure 1. Flow chart of the study selection process for systematic review of animal protein sources as a substitute for fishmeal in aquaculture diets.

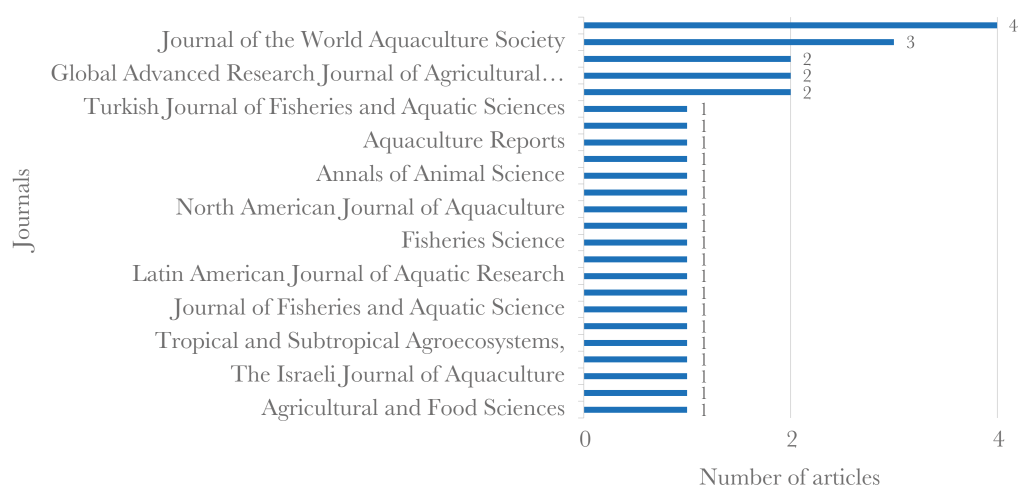

Figure 2. Scientific journals that have published research on the use of agro-industrial by-products as alternative ingredients in fish diets.

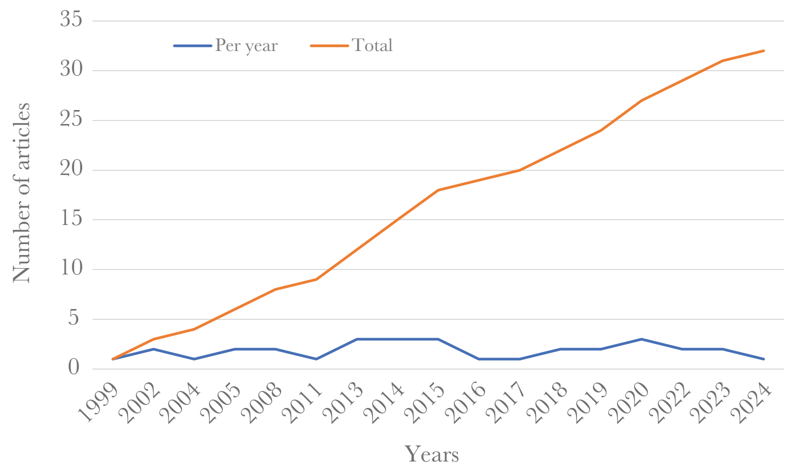

Figure 3. Annual (blue) and cumulative (red) evolution of the number of publications between 1999 and 2024 on the use of by-products in fish diets, compared to fishmeal-based diets.

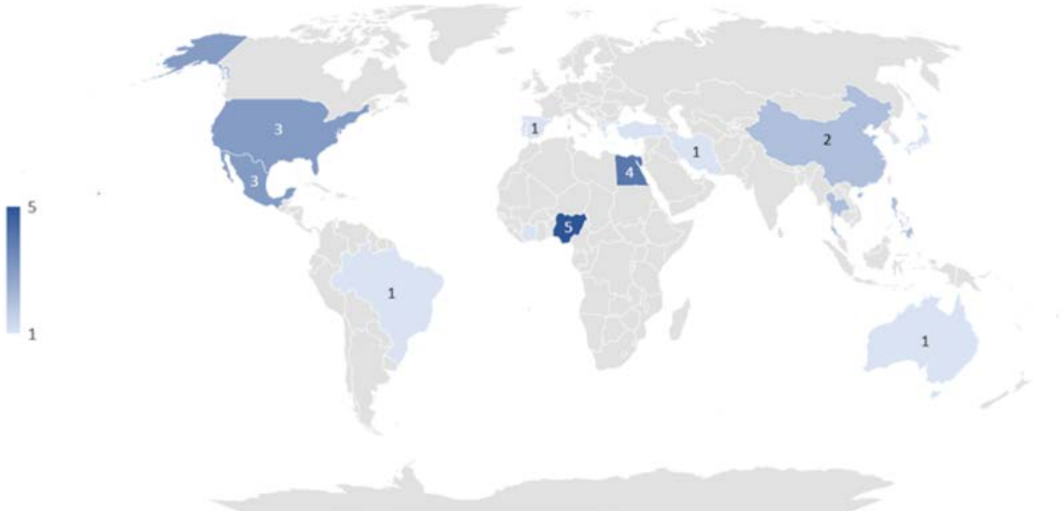

Figure 4. Number of articles and countries that publish most on this topic.

Egypt followed with four studies, while Mexico and the United States each contributed three, reflecting North America's active role in evaluating protein alternatives. China, despite its global leadership in aquaculture production, contributed only two studies, which is nevertheless notable. Other countries, including Brazil, the Philippines, Iran, Spain, and Australia, published one article each, demonstrating a growing but still incipient global diversification of research efforts. This distribution also reflects that the development of alternative ingredients depends largely on the availability of local resources and the production models implemented in each country. Figure 5 presents a word cloud of the most frequent terms found in the studies included in this review, with "diet" and "protein" being the most predominant.

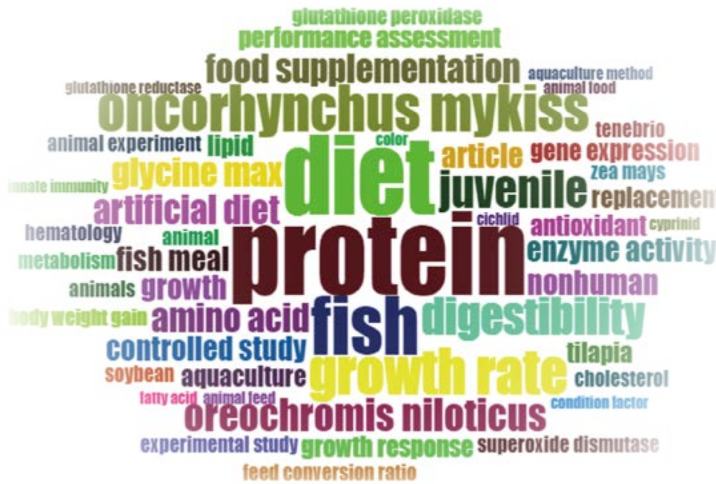

Figure 5. Word cloud of the most frequently occurring words in the studies included in the review.

The selected studies addressed the use of agro-industrial by-products as partial or total substitutes for fishmeal in aquafeeds. These were grouped into six main categories: vegetable by-products, terrestrial animal by-products, fishery by-products, hydrolyzed meals, bioprocessed meals, and microbial biomass (Table 1). Overall, the evidence indicates that a wide variety of by-products can be successfully integrated into aquaculture formulations, if factors such as the target species, inclusion level, nutritional quality of the by-product, and pre-processing method are appropriately considered. This diversity of approaches highlights the growing interest in reducing dependence on fishmeal and advancing toward more sustainable and cost-effective aquaculture production systems. Among vegetable by-products, brewer's waste has proven particularly effective in diets for *Oreochromis niloticus*, allowing up to 50% of fishmeal protein to be replaced while maintaining a feed conversion advantage (FCA) of 1.9 and 100% survival. In contrast, by-products such as lemon peel exhibited limited efficacy, with a total conversion efficiency (TCE) of only 0.2% and an FCA of 19.6. Regarding terrestrial animal by-products, poultry by-product meal emerged as one of the most efficient alternatives, enabling up to 100% replacement in species such as *Morone chrysops* × *saxatilis* and *Oreochromis niloticus* without compromising growth performance or feed efficiency.

By-products from the aquaculture industry, presented as silages or hydrolyzed meals, were also found to be effective. Silage from *Pterygoplichthys multiradiatus* in *Oreochromis niloticus* achieved total conversion efficiency (TCE) of 4.0 and a feed conversion advantage (FCA) of 1.7, while hydrolyzed meals, such as those from tuna by-products or *Lophius vomerinus*, exhibited FCAs of 1.1 and 0.8, respectively, with high survival rates. Bioprocessed meals treated with microorganisms, including *Saccharomyces cerevisiae* and *Lactobacillus casei*, demonstrated notable improvements in both digestibility and productive performance. In *Lates calcarifer*, a diet containing 75% bioprocessed poultry by-product meal reached a TCE of 5.1 and an FCA of 1.1. Finally, the inclusion of bacterial biomass, such as *Rubrivivax gelatinosa*, at low doses (0.5%) had a positive functional effect in tilapia, yielding an FCA of 1.1.

Table 1.

Protein sources that replace fishmeal	Fish species	Optimal level (%)	Duration of experiment (days)	Feeding frequency (times/day)	Initial weight (g)	Results for recommended levels				Citation
						Final weight (g)	Survival (%)	Specific growth rate (%)	Feed conversion ratio	
Vegetable by-products										
Corn bran	*Sarotherodon melanotheron*	NR	180	1	1.2±0.0	17.2±1.8	59	NR	7.8±0.6	[20]
Brewery waste	*Oreochromis niloticus*	5	70	NR	23.8±0.9	76.9±2.3	100	NR	1.9±0.0	[15]
Peanut shell (*Arachis hypogaea* L.)	*Oreochromis niloticus*	20	56	2	4.2±0.2	16.2±0.8	90	2.3±0.1	2.3±0.2	[21]
Lemon peel (*Citrus lemon*)	*Oreochromis niloticus*	1	45	2	28.9±0.3	31.7±1.3	72	0.2±0.0	19.6±4.6	[14]
By-products of *Gracilaria* sp.	*Sparus aurata*	2.5	59	2	10.2±0.2	27.83±0.6	NR	1.6±0.0	1.0±0.0	[22]
Wine by-products	*Liza aurata*	10	42	5	65.4±0.0	87.7±1.1	NR	1.0±0.0	NR	[23]
Land animal by-products										
Poultry by-product meal	*Scophthalmus maeoticus*	2	60	2	18.0±0.0	29.3±0.7	100	0.8±0.0	0.9± 0.0	[24]
Poultry by-product meal	*Morone chrysops* × *saxatilis*	1	246	1	5.6	499±0.0	81	1.8±0.0	2.5±0.0	[25]
Poultry by-product meal	*Lutjanus guttatus*	25	84	3	11.0±0.0	36.1±2.5	100	1.4±0.0	1.2±0.0	[26]
Poultry by-product meal	*Oreochromis niloticus*	10	120	2	1.5±0.0	54.3±1.5	NR	2.9±0.3	1.3±0.1	[27]
Poultry by-product meal	*Dicentrarchus labrax*	6	70	3	0.7±0.0	8.2±0.1	94	3.5±0.0	2.2±0.1	[28]
Poultry by-product meal	*Centropristis striata*	8	56	2	1.2±0.0	15.9±0.3	100	2.4±0.0	1.0±0.0	[29]
Poultry by-product meal	*Takifugu obscurus*	7	56	2	17.1±1.83	57.9±2.7	95	2.19±0.1	0.9±0.0	[30]
Feather meal	*Clarias gariepinus*	20	30	2	NR	NR	88	7.7±0.3	±	[31]
Feather meal	*Oncorhynchus mykiss*	25	72	2	569.8±9.5	1299.0±91.6	100	1	0.87±0.0	[32]
Blood meal	*Clarias gariepinus*	5	86	2	8.8±2.9	66.5±13.4	100	1.0±0.0	0.8±0.1	[33]
Meat and bone meal	*Ophiocephalus argus*	2	70	3	12.1±0.0	138.6±2.3	94	3.4	1.24±0.0	[34]
Meat and blood meal	*Epinephelus coioides*	8	60	2	6.1±0.5	NR	99	2.9±0.3	1.04±0.0	[35]
By-products of the aquaculture industry										
Silage of *Pterygoplichthys multiradiatus*	*Oreochromis niloticus*	15	50	3	1.5±0.7	11.4±1.4	98	4.0±0.2	1.7±0.1	[13]

Table 1. Continues...

Protein sources that replace fishmeal	Fish species	Optimal level (%)	Duration of experiment (days)	Feeding frequency (times/ day)	Initial weight (g)	Results for recommended levels				Citation
						Final weight (g)	Survival (%)	Specific growth rate (%)	Feed conversion ratio	
Silage of *Pseudoplatystoma* sp.	*Oreochromis niloticus*	12	30	4	4.2±0.1	NR	10	NR	1.3±0.1	[36]
Fish waste silage	Red tilapia (*Oreochromis mossambicus* × *Oreochromis niloticus* × *Oreochromis aureus*)	50	84	NR	2.1±0.0	28.0	NR	3.0±0.1	1.3±0.1	[16]
Tuna by-product hydrolysate	*Pagrus major*	50	56	2	0.8±0.1	28.5±0.3	95	NR	1.1±0.0	[37]
Shad by-product hydrolysate	*Epinephelus fuscoguttatus*	15	56	2	2.9±0.2	31.2±1.4	100	NR	1.4±0.0	[38]
Lophius vomerinus protein hydrolysate	*Clarias gariepinus*	2	70	3	0.9±0.0	32.0±0.3	10	5.0±0.0	0.8±0.0	[39]
Stickwater	*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*	20	56	4	5 g	672	100	NR	0.802	[40]
Flour mix										
Poultry by-product meal and soybean meal	*Morone chrysops* × *saxatilis*	10	56	2	15	71.9±4.0	100	2.8±0.1	2.1±0.1	[41]
Cottonseed meal, soybean meal and animal by-product mixture	*Oncorhynchus mykiss*	100	112	3	0.9±0.0	NR	NR	2.3±0.0	0.9±0.0	[42]
Tuna by-product meal, poultry by-product meal and meat meal	*Paralichthys olivaceus*	50	56	2	18.0±0.0	91.6±0.2	100	2.9±0.0	NR	[43]
Bioprocessed flours										
Bioprocessed poultry by-product meal with *Saccharomyces cerevisiae* and *Lactobacillus casei*	*Lates calcarifer*	75	42	NR	3.7±0.1	33.7±1.2	86	5.1±0.0	1.1±0.0	[44]
Fermented poultry by-product meal with *Saccharomyces cerevisiae*	*Cyprinus carpio*	20	90	2	4.9±0.0	14.5±0.1	98	1.8±0.0	1.5±0.0	[45]
Microbial biomass										
Rubrivivax gelatinosa	*Oreochromis niloticus*	0.5	72	3	27.4±1.3	244.0±10.6	NR	NR	1.1±0.0	[19]

Other animal-derived meals, including blood meal, meat and bone meal, and feather meal, also demonstrated favorable results, characterized by low FCA values (up to 0.8) and high TCE (up to 3.5%).

This systematic review demonstrates the growing interest and potential of using by-products as alternative ingredients in aquaculture diets, reflecting both economic and environmental pressures to reduce reliance on fishmeal, one of the most expensive and environmentally sensitive inputs in aquaculture [4]. The increasing number of publications since 2013, particularly between 2015 and 2022, highlights a rising awareness among researchers and producers of the need to adopt sustainable practices in line with global circular economy goals. The geographical distribution of studies, with notable contributions from developing countries such as Nigeria and Egypt, underscores the role of locally available by-products in reducing production costs and supporting emerging aquaculture systems. From a nutritional perspective, the efficacy of by-products is largely determined by their origin, composition, processing method, and inclusion level [12].

Land animal by-products, particularly poultry by-product meal, consistently demonstrate high efficiency and compatibility with the dietary requirements of carnivorous and omnivorous fish, even at complete replacement levels [3]. However, their widespread use may be constrained by regional availability, regulatory restrictions, or competition with other livestock industries. Additionally, although the use of animal by-products supports circular economy objectives, the environmental benefits may be limited if the source originates from intensive poultry or pig production systems [1]. Vegetable by-products offer advantages in terms of cost, accessibility, and environmental perception, but their high fiber content, anti-nutritional factors, and limited essential amino acid profile can restrict their use [5]. The poor performance of lemon peel, with an extremely high FCR (19.6), illustrates the risks of incorporating ingredients without adequate evaluation of digestibility, toxicity, or palatability [14].

Conversely, ingredients such as brewer's waste demonstrate potential if inclusion levels respect the physiological limits for protein utilization in fish [15]. Fishery by-products, including silages and hydrolyzed meals, are highly compatible with fish digestive physiology due to their provision of readily digestible peptides [16]. These results reinforce the value of post-harvest processing for enhancing the utility of by-products, particularly in regions with active fisheries. Nevertheless, logistical challenges such as cold storage requirements, microbiological stability, and producer acceptance remain barriers to large-scale adoption [17]. Emerging strategies, such as bioprocessed flours and microbial biomass, show promise in improving digestibility, functional properties, and even nutraceutical value. Fermentation with beneficial microorganisms enhances growth and feed conversion efficiency, sometimes exceeding the performance of traditional fishmeal-based diets [18]. Moreover, bacterial biomass, such as *Rubrivivax gelatinosa*, offers the potential to deliver bioactive compounds with immunostimulatory or antioxidant effects. However, these approaches require further validation under commercial conditions and comprehensive cost-benefit analyses before they can be widely implemented [19]. Overall, the evidence suggests that a diversified approach combining animal, plant, fishery, and bioprocessed by-products may offer the most viable strategy for sustainable aquaculture, balancing nutritional adequacy, economic feasibility, and environmental responsibility. Future research should focus on optimizing inclusion levels, processing techniques, and functional benefits while addressing logistical and regulatory constraints to facilitate the practical adoption of these alternative ingredients.

CONCLUSION

In conclusion, the findings highlight a clear shift towards a more diversified and sustainable aquaculture sector using by-products that have been underutilized in recent decades. The successful adoption of these alternative ingredients will depend on achieving a balance between technical feasibility, cost-effectiveness, supply stability, and market acceptance. Advancing processing technologies, optimizing diet formulation, and conducting comprehensive evaluations that consider not only production performance but also environmental, health, and economic aspects will be crucial to fully realize the potential of by-products in sustainable aquaculture.

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