

ROLE OF FUNCTIONAL FEED ADDITIVES IN REDUCING NUTRIENT POLLUTION IN AQUACULTURE SYSTEMS

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Introduction

Aquaculture has emerged as the fastest-growing food production sector, making a significant contribution to global food security and the increasing demand for high-quality aquatic protein (FAO, 2026). To meet this demand, production systems have become increasingly intensive through higher stocking densities and greater reliance on formulated feeds. Although intensification has substantially improved productivity, it has also increased environmental concerns associated with nutrient-rich effluents, disease outbreaks, and the sustainable use of feed resources (Naylor et al., 2021; Boyd et al., 2020).

Feed is the primary nutrient input in intensive aquaculture and accounts for nearly 50–70% of production costs. Fish require a dietary crude protein level of 25–50%, yet less than half of the nitrogen and phosphorus consumed is retained in their bodies (Piedrahita, 2003). The remainder is released into the water, where it contributes to environmental pollution. Nitrogen is primarily excreted as ammonia, while phosphorus is released as particulate matter, both of which can degrade water quality and disrupt aquatic ecosystems. The amount of nitrogen and phosphorus retained by the fish varies, with average nitrogen retained ranging from between 25% and 30% (Boyd, 2003) to 10%–49% (Piedrahita, 2003) and 17–40% for phosphorus retention (Piedrahita, 2003), while the remaining nutrients are released into the culture environment through uneaten feed, faeces, and metabolic excretion. Subsequently, excess P in aquafeed yields in higher levels of excreted P. This is a major cause of eutrophication in ponds often resulting in impaired water quality downstream. The accumulation of these nutrients,

together with organic wastes, contributes to eutrophication, harmful algal blooms, oxygen depletion, sediment deterioration, and reduced ecological carrying capacity of aquatic ecosystem.

The increasing replacement of fishmeal and fish oil with plant-based ingredients has further intensified this challenge. Although plant proteins improve the sustainability and economic viability of aquafeeds, they contain antinutritional factors such as phytate, non-starch polysaccharides, tannins, lectins, and protease inhibitors that reduce nutrient digestibility and mineral bioavailability. Consequently, a greater proportion of dietary nutrients, particularly phytate-bound phosphorus, remains undigested and is excreted into the aquatic environment, increasing nutrient loading and environmental pollution (Francis et al., 2001; Debnath et al., 2005; Lemos & Tacon, 2017).

Various engineering and management approaches, including recirculating aquaculture systems (RAS), biofloc technology, integrated multi-trophic aquaculture (IMTA), and precision feeding, have been developed to reduce nutrient discharge. However, these strategies mainly manage or treat wastes after they are generated and often require substantial infrastructure and operational costs. In contrast, nutritional interventions such as optimizing feed formulation, feeding management practices, feed processing, appropriate choice of ingredients, and using functional feed ingredients etc., that improve nutrient utilization at the source have gained increasing attention as a more sustainable and cost-effective approach to pollution mitigation (Musalia et al., 2020).

Among these nutritional interventions, functional feed additives have emerged as an effective strategy for improving feed efficiency while minimizing environmental pollution. Additives such as exogenous enzymes, probiotics, prebiotics, synbiotics, organic acids, and phytogenic compounds enhance nutrient digestibility, improve gut health, and increase nutrient retention, thereby reducing the release of nitrogen, phosphorus, and organic wastes into aquaculture waters (Onomu & Okuthe, 2024; Bharathi et al., 2019).

Functional Feed additives?

Additives in aquafeed are nutritive/nonnutritive ingredients that are supplemented in small amounts (alone or in combination) for a specific purpose, such as to improve the quality of fish as a final product, to preserve the physical and chemical quality of the diet, or to maintain

the quality of the aquatic environment (Bai et al., 2015). The functional feed additives improve growth, immune response; induce the physiological functions and health performance of the fishes over the normal feed additives. Functional feed additives include phytochemicals, binders, organic acids, immune – stimulants, yeast products, probiotics, prebiotics, enzymes etc. Lowering feed conversion ratios (FCR) reduces production costs and nutrient waste, directly enhancing aquaculture's economic and environmental sustainability. Among all the above, exogenous enzymes, pro and prebiotics, binders, and organic acids play the major role in reducing the nutrient pollution in aquaculture.

1. Exogenous enzymes

Exogenous enzymes are widely used as feed additives in aquaculture including protease, lipase, carbohydrate enzymes, and phytase (Zheng et al., 2020)

- **Phytase**

Phytase is one of the most effective exogenous enzymes used in aquaculture to improve phosphorus utilization and reduce phosphorus discharge into aquatic environments. In plant-based aquafeeds, approximately 60–80% of phosphorus exists as phytate, which is poorly digested by most cultured fish because of their limited endogenous phytase activity (Jobling et al., 2001; Cao et al., 2007). Consequently, a significant proportion of dietary phosphorus is excreted into culture waters, contributing to nutrient enrichment and eutrophication (Debnath et al., 2005; Lemos & Tacon, 2017).

Supplementation of exogenous phytase hydrolyses phytate, releasing bioavailable phosphorus and reducing its binding with proteins, amino acids, and essential minerals. This improves phosphorus digestibility, enhances nutrient utilization, and decreases the requirement for inorganic phosphorus supplementation, thereby reducing phosphorus losses through faecal excretion and the environmental phosphorus load (Cao et al., 2007; Kumar et al., 2012; Zheng et al., 2020). The large majority of studies involving the use of phytases in aquafeeds have been with microbial phytases derived from *Aspergillus* species; phytases generally used in the form of a dry powder or liquid form (Kumar et al. 2012), although free or encapsulated forms have also been used (Vandenberg et al. 2011). However, the efficacy of phytase is influenced by factors such as enzyme source, dietary phytate concentration, feed processing conditions, supplementation level, and fish species (Hussain et al., 2017).

- **Protease**

Hydrolyses dietary proteins into absorbable peptides and amino acids, thereby improving protein utilization. Since undigested dietary protein is excreted as nitrogenous waste, inefficient protein digestion contributes to ammonia accumulation and nutrient pollution in aquaculture waters (Zheng et al., 2020). By enhancing protein digestibility and nitrogen retention, exogenous proteases reduce nitrogen discharge while improving feed efficiency, making them an effective nutritional strategy for reducing the environmental footprint of fed aquaculture (Liang et al., 2022).

2. Organic Acids

Organic acids are weak carboxylic acids that improve nutrient utilization by lowering the gastrointestinal pH, enhancing digestive enzyme activity, and modulating the intestinal microbiota. Commonly used organic acids in aquaculture include formic, propionic, butyric, citric, lactic, and acetic acids and their salts (Ng & Koh, 2017; Bharathi et al., 2019). By suppressing pathogenic bacteria and promoting a favourable gut environment, organic acids improve nutrient digestibility and feed efficiency, thereby reducing the excretion of undigested nutrients and organic wastes into aquaculture waters. Consequently, dietary organic acids contribute to lower nutrient loading, improved water quality, and enhanced environmental sustainability of fed aquaculture (Ng & Koh, 2017).

3. Binders

Binders are technological feed additives that improve pellet integrity and water stability, thereby reducing feed disintegration and nutrient leaching before feed consumption. Commonly used binders in aquafeeds include plant-based binders (starch, guar gum and alginate), animal-derived binders (gelatin and collagen), mineral binders (bentonite), and synthetic binders such as carboxymethyl cellulose (CMC) (Hardy & Barrows, 2003; Karim et al., 2022). By maintaining pellet cohesion, binders minimize the loss of soluble nutrients, particularly nitrogen and phosphorus, into the culture water and reduce the accumulation of organic matter from uneaten or fragmented feed. Improved pellet stability also enhances nutrient retention within faecal particles, facilitating waste removal and reducing dissolved nutrient release into the environment. Consequently, binders improve feed utilization, maintain water quality, and contribute to reducing the environmental footprint of intensive aquaculture (Hafeez et al., 2024).

4. Probiotics and prebiotics

Probiotics are beneficial live microorganisms, whereas prebiotics are non-digestible feed ingredients that selectively stimulate the growth and activity of beneficial gut microbiota. Common probiotics used in aquaculture include species of *Bacillus*, *Lactobacillus*, *Lactococcus*, *Enterococcus*, *Pseudomonas*, and *Saccharomyces*, while widely used prebiotics include mannan oligosaccharides (MOS), fructooligosaccharides (FOS), galactooligosaccharides (GOS), inulin, arabinoxylan oligosaccharides (AXOS), and β -glucans (Ringø et al., 2010; Hai, 2015).

Both probiotics and prebiotics improve gut microbial balance, enhance digestive enzyme activity, and increase nutrient digestibility, resulting in better feed utilization and nutrient retention. They also suppress pathogenic microorganisms through competitive exclusion and the production of antimicrobial compounds, promoting intestinal health and improving feed conversion efficiency (Ringø et al., 2010; Hai, 2015). Consequently, improved nutrient assimilation reduces the excretion of nitrogen, phosphorus, and organic wastes into aquaculture waters, thereby lowering nutrient loading, improving water quality, and enhancing the environmental sustainability of fed aquaculture (Okon et al., 2025; Onomu & Okuthe, 2024).

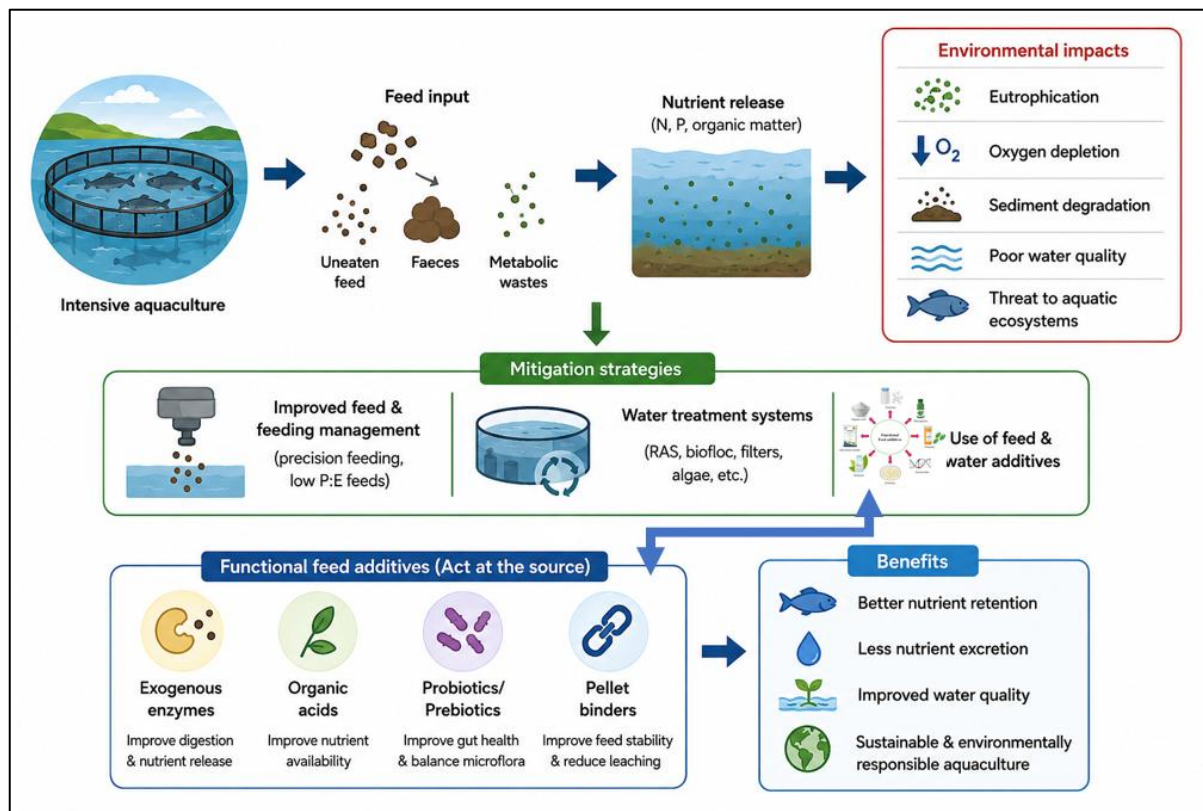


Fig. 1: Pathways of nutrient pollution in aquaculture and mitigation through feed additives

Table 1: Role of some of the feed additives in reducing the environmental pollution in aquaculture

Feed additive	Species	Inclusion level	Environmental benefit	Reference
Phytase	Rainbow trout (<i>Oncorhynchus mykiss</i>)	4000 FTU kg ⁻¹ diet	Reduced nitrogen and phosphorus loadings by 13% and 50% , respectively	Morales et al. (2016)
	African catfish (<i>Clarias gariepinus</i>)	2000 FTU kg ⁻¹ diet	Reduced phosphorus loading by 31%	Olugbenga et al. (2017)
Protease	Whiteleg shrimp (<i>Litopenaeus vannamei</i>)	200 mg kg ⁻¹ diet	Improved protein digestibility and nitrogen retention; significantly reduced total ammonia nitrogen (TAN) excretion; improved FCR and PER	Santigosa et al. (2026)
	Gibelion carp (<i>Carassius auratus gibelio</i>)	150 and 175 mg kg ⁻¹ diet	Improved nutrient digestibility and retention with reduced FCR, indicating lower nitrogen waste	Shi et al. (2016)
Formic acid	Rainbow trout (<i>Oncorhynchus mykiss</i>)	-	Improved phosphorus digestibility and utilization	Vielma & Lall (1997)
Citric acid	Sea bream	-	Enhanced nitrogen and phosphorus retention	Hossain et al. (2007)
	Sturgeon	-	Increased calcium and phosphorus bioavailability, improving phosphorus utilization	Khajepour & Hosseini (2012)
Binder (guar gum)	Sea cucumber (RAS)	5% of feed	Reduction of 24.8% Total Nitrogen 38.5% Total Phosphorus 0.08–0.18 mg/L Ammonia-N	Zhou et al. (2026)

Conclusion

The increasing intensification of aquaculture has heightened nutrient pollution due to inefficient feed utilization, resulting in the discharge of nitrogen, phosphorus, and organic wastes into culture waters. Functional feed additives provide an effective nutritional strategy to address this challenge by improving nutrient digestibility, retention, and feed conversion efficiency. Exogenous enzymes, organic acids, pellet binders, and probiotics/prebiotics reduce nutrient losses, minimize feed wastage, and improve water quality, thereby lowering the environmental footprint of aquaculture. Improved feed utilization also reduces feed conversion ratio (FCR), decreasing feed requirements, production costs, and nutrient-rich effluent discharge. Therefore, the strategic incorporation of functional feed additives into aquafeeds not only enhances environmental sustainability but also improves the economic viability and long-term sustainability of intensive aquaculture systems.

Reference

- Bai, S. C., Katya, K., & Yun, H. (2015). Additives in aquafeed: An overview. *Feed and feeding practices in aquaculture*, 171-202.
- Bharathi, S., Antony, C., Cbt, R., Arumugam, U., Ahilan, B., & Aanand, S. (2019). Functional feed additives used in fish feeds. *Int. J. Fish. Aquat. Stud*, 7(3), 44-52.
- Debnath D, Pal AK, Sahu NP, Jain KK, Yengkokpam S, Mukherjee SC (2005) Effect of dietary microbial phytase supplementation on growth and nutrient digestibility of *Pangasius pangasius* (Hamilton) fingerlings. *Aquac Res* 36:180–187
- FAO. 2026. *The State of World Fisheries and Aquaculture 2026 – Blue Transformation: turning vision into impact*. Rome. <https://doi.org/10.4060/cd8357en>
- Hardy, R. W., and Barrows, F. T. (2003). Diet formulation and manufacture. In *Fish nutrition* (pp. 505-600). Academic Press.
- Karim, A., Naila, B., Khwaja, S., Hussain, S. I., and Ghafar, M. (2022). Evaluation of different Starch Binders on physical quality of fish feed pellets. *Brazilian Journal of Biology*, 84, e256242. <https://doi.org/10.1590/1519-6984.256242>.
- Lemos, D., & Tacon, A. G. (2017). Use of phytases in fish and shrimp feeds: a review. *Reviews in Aquaculture*, 9(3), 266-282. <https://doi.org/10.1111/raq.12138>

- Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., ... & Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, 591(7851), 551-563. <https://doi.org/10.1038/s41586-021-03308-6>
- Ng, W.-K. and Koh, C.-B. (2017), The utilization and mode of action of organic acids in the feeds of cultured aquatic animals. *Rev Aquacult*, 9: 342-368. <https://doi.org/10.1111/raq.12141>
- Okon, E., Iyobhebhe, M., Olatunji, P., Adeleke, M., Matekwe, N., & Okocha, R. (2025). Feed additives in aquaculture: benefits, risks, and the need for robust regulatory frameworks. *Fishes*, 10(9), 471.
- Shi, Z., Li, X. Q., Chowdhury, M. A. K., Chen, J. N., & Leng, X. J. (2016). Effects of protease supplementation in low fish meal pelleted and extruded diets on growth, nutrient retention and digestibility of gibel carp, *Carassius auratus gibelio*. *Aquaculture*, 460, 37–44. <https://doi.org/10.1016/j.aquaculture.2016.03.049>
- Zhou, Y., Song, C., Li, Q., Du, L., Li, X., Dong, D., ... & Song, X. (2026). Reducing nitrogen and phosphorus discharges from sea cucumber-based recirculating aquaculture system through dietary binder addition. *Aquaculture Reports*, 46, 103299.