

## Enzymes for aquaculture productivity: a mini review

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**Abstract.** Aquaculture plays a vital role in providing protein-rich food, but its high production levels generate significant waste, including organic and inorganic matter. Enzyme technology offers a promising solution for managing this waste, leveraging their high specificity and catalytic properties to facilitate efficient biological transformations. This article provides an overview of enzyme applications in aquaculture, including supplementation in feed, immunomodulatory effects, and waste management. This study aimed to highlight the potential of enzymes in promoting sustainable aquaculture development. This review examined how enzymes play a crucial role in aquaculture by enhancing nutrient absorption and waste management. They facilitate the breakdown of complex feed molecules into easily digestible forms, thereby improving fish nutrition and reducing waste. Furthermore, some enzymes also help manage waste by breaking down organic matter, improving water quality. Eco-enzymes or bio-enzymes, derived from organic matter such as fruits and vegetables, can be utilized in a symbiotic approach, combining probiotics and prebiotics to enhance host health and growth. Enzymes in aquaculture can specifically target pollutants, enabling efficient and precise removal of contaminants from the environment. As biological catalysts, enzymes accelerate chemical reactions, enabling efficient decomposition, pollutant breakdown, and detoxification processes. Adding external enzymes (exogenous enzymes) can enhance microbial degradation of pollutants by triggering the production of internal enzymes. It enhanced contaminant degradation and detoxification, improving water quality through decomposition and pollutant removal.

**Key Words:** biocatalyst, decontamination, organic waste.

**Introduction.** Aquaculture is a rapidly expanding sector within the global food industry (Obirikorang et al 2024). As a primary industry, aquaculture is an important sector for the economy in many parts of the world. One of the factors driving the growth of aquaculture production is the paradigm shift in consumer preferences for quality protein-rich foods, especially those derived from fish protein (Wasik et al 2025). The increasing population and the increasing demand for fish consumption have an impact on the exploitation of production in the fish farming industry sector (Bazarova et al 2023).

The fish feed industry is part of an industry that grows along with the increase in aquaculture production in order to meet the needs of fish for consumers (Islam et al 2024). Feed containing organic materials, one of which is protein with a high percentage, greatly supports fish growth and productivity. However, sometimes uncontrolled feeding management has a negative impact on fish (Taşbozan 2023; Ndebele-Murisa et al 2024). One mistake that is often made in feeding management is that the quantity of feed given is very excessive compared to the needs of the fish. This causes the excess feed to dissolve or accumulate in the waters (Filbrun et al 2013; Ballester-Moltó et al 2017). The presence of excess organic material in water can cause various adverse effects on the aquatic environment which will directly or indirectly impact to cultured-fish health and productivity (Malik et al 2020; Yusoff et al 2024).

In addition, the development of the blue bioeconomy that emphasizes sustainable resources for economic growth and development, requires the aquaculture sector to adapt to these major sustainability challenges and issues. One of the main challenges is that the organic waste produced must be properly processed so as not to pose a serious threat to the environment and especially to human health. The concept of the blue bioeconomy is very concerned with the importance of minimizing and/or eliminating waste production (Boyd et al 2020; Khiari 2024).

The addition of extracellular hydrolytic enzymes has generally played an important role in water management through the degradation of organic matter. This enzymatic activity involves microbes in the natural aquatic environment to decompose the organic matter contamination (Sakami et al 2005). Insoluble complex organic matter in waters is hydrolyzed by extracellular enzymes to prevent the increase in high organic waste in the waters due to the anaerobic digestion rate of high-content organic waste (Zhang et al 2007). Furthermore, Ravindran and Son (2011) revealed the use of enzyme is the important key for sustainable aquaculture development. The enzyme contributes as essential ingredient in the fish feed. Liang et al (2022) explained the addition of enzymes to fish feed has a positive impact on the availability of feed that has the number of calories and essential nutrients. Nutrients that are available in good quantity and quality can produce optimal growth for farmed fish. Enzymes that enter the digestive tract of fish can also increase the process of decomposition, digestion, and absorption of food nutrients in the digestive tract of fish.

The added extracellular enzymes can also increase the role of microbes, including autochthonous (indigenous microflora) and allochthonous (added microflora) in the digestive tract by producing hydrolysis enzymes from the microbes themselves. The enzymes produced by these microbes will help accelerate the series of processes from decomposition to absorption of feed (Ganguly & Prasad 2012). Fish gut microbiota produces various endogenous enzymes such as amylase, lipase, cellulase, protease, chitinase etc. and these enzymes play a significant role as exogenous for fish. Furthermore, the symbiotic of gut microbe and the healthy digestion track contribute to immunity and metabolic strength of fish (Sarmah & Kardong 2022; Jiao et al 2023).

This article reviewed the use of enzymes in aquaculture based on existing literature. The findings of this research are expected to highlight the crucial role of enzymes in advancing sustainable practices in aquaculture.

## **Material and Method**

**Literature review.** The cited articles are relevant scientific articles for this topic. We gathered and cited 119 articles that were published from 2002 to 2025, related to enzyme, aquaculture, organic waste, role of enzyme for aquaculture productivity, and other relevant articles. The collected information of those articles was systematically analyzed from Google Scholar to ensure a comprehensive and detailed review.

The information gathered from the cited literature will concentrate on the function of enzymes in managing organic waste within the aquaculture sector, with the goal of improving aquaculture productivity.

**Enzyme.** Enzymes are biomolecules in the form of macromolecules or complex proteins that work on substrate molecules with specific biochemical activities (Garcia-Quinto et al 2023). Enzymes facilitate chemical reactions by lowering the activation energy barrier (Stein 2006). The ability of enzymes as biological components to catalyze chemical reactions makes them known as biocatalysts that can be used for many fermentation, reduction, decomposition, and other reactions (Robinson 2015; Kulkarni 2022). There are seven classes of enzyme according to the properties of the reactions catalyzed by enzymes, namely oxidoreductases (EC1), transferases (EC2), hydrolases (EC3), lyases (EC4), isomerases (EC5), ligases (EC6), and translocases (EC7) (Tao et al 2020; McDonald & Tipton 2023).

Oxidoreductases catalyze or facilitate reduction and oxidation (redox) reactions by transferring electrons from a donor to an acceptor (El-Gendi et al 2021; Yang et al 2023).

Enzymes like oxidases, dehydrogenases, peroxidases, and oxygenases are extensively studied for their potential in diverse biocatalytic processes (Cárdenas-Moreno et al 2023).

Transferases facilitate the transfer of functional groups, such as amine and phosphoryl groups, between molecules, playing a key role in various biochemical reactions (Mulikidjanian & Galperin 2009). Transaminases, for instance, catalyze the transfer of amino groups from donors to acceptors (Caligiore et al 2022).

Hydrolases represent the largest and most varied class of enzymes. Hydrolase are involved in breaking different chemical bonds by utilize water as a hydroxyl group donor in diverse substrates of different sizes and complexity such as proteins, carbohydrates, lipids, and nucleic acids (Sousa et al 2015). This enzyme is able to catalyze multiple transformations in both aqueous medium and organic solvents (Méndez-Sánchez et al 2016). Several hydrolase subclass enzymes are protease, lipase, amylase, cellulase, xylanase etc. (Ismail et al 2025).

Lyases are a class of enzymes that mediate bond formation and breakage through mechanisms distinct from hydrolysis and redox reactions, producing compounds with novel cyclic or double bond structures (Mathieu et al 2013). This class was categorized into four subclasses, namely carboxy lyases, aldehyde lyases, oxoacid lyases, and other carbon-carbon lyases (Brovetto et al 2011).

Isomerases catalyze intramolecular rearrangements by facilitating the transfer of specific groups, thereby altering molecular structure (Gurung et al 2013). For instance, glucose isomerase, also known as xylose isomerase, reversibly converts D-glucose and D-xylose to D-fructose and D-xylulose, respectively (Nam 2022).

Ligases join two molecules by creating new chemical bonds, which can be categorized into different types, including C-C, C-N, C-S, C-O, N-metals, and P-ester bonds (El-Gendi et al 2021). For example, DNA ligases catalyze the creation of phosphodiester bonds, linking 5' phosphates and 3' hydroxyl groups in DNA (Gundesø et al 2024).

Translocases enable the movement of ions or molecules across or within membranes. Notably, helicases and nucleic acid translocases are crucial for DNA replication and chromatin remodeling (Lohman et al 2008; McDonald & Tipton 2023).

Enzyme action can be described by two primary models: the lock-and-key model and the induced-fit model. The lock and key model suggests a static, rigid fit between the enzyme's active site and the substrate, while the induced fit model proposes that the enzyme's active site can change shape upon substrate binding to optimize the interaction (Gouseti et al 2023). The illustration model of enzyme action was shown in Figure 1.

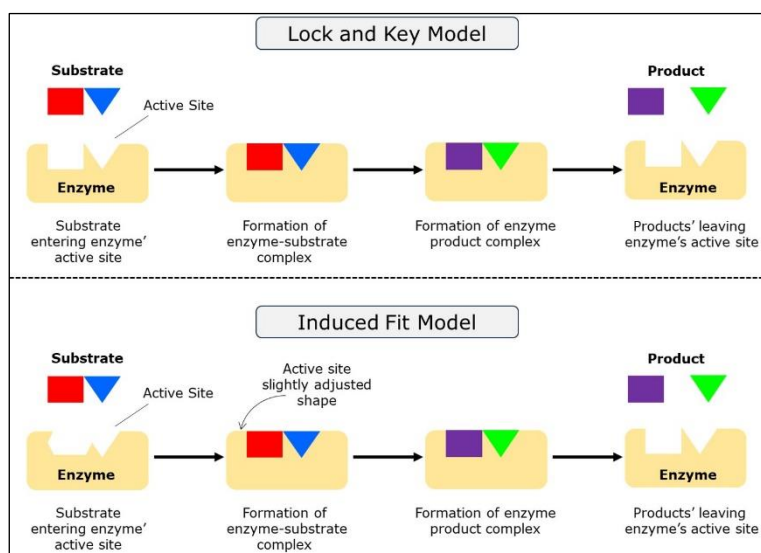


Figure 1. Enzyme action models describe how enzymes interact with substrates to produce products. The lock-and-key model proposes a precise fit between the active site and substrate, whereas the induced-fit model suggests that the active site adapts to fit the substrate perfectly (redrawn from Siddikey et al 2025).

**Enzymes added in fish feed.** Fish nutrition and feeding strategies have a profound impact on their overall health, growth, reproduction, and ability to cope with environmental stressors and disease (Lall & Tibbetts 2009). A fish takes its needs from macronutrients such as dietary lipids, protein, and carbohydrate in feed (Stone 2003; Manam 2023).

Fish farming requires feed that is easily digestible by enzymes to provide optimal nutrition. Non-fish ingredients, which are often rich in high molecular weight organic matter, can be difficult for fish to digest (Liang et al 2022).

One approach, the addition of enzymes to feed, has been widely used to enhance nutrient utilization, improve digestibility, and promote more efficient aquaculture practices. Enzymes play an important role in improving nutrient absorption and digestive efficiency in fish feeds. Supplementing fish feed with exogenous enzymes can enhance nutrient utilization, degrade anti-nutritional factors, and improve digestion by complementing the natural enzymes produced by fish (Jannathulla et al 2019; Maser et al 2025).

Exogenous enzymes, including protease, lipase, carbohydrate enzyme and phytase, are widely used as additives in improvement of fish feed (Zheng et al 2019; Liang et al 2022). Exogenous enzyme can compensate for the deficiency of endogenous enzymes and help break down macromolecular that are difficult to digest (Shi et al 2016; Saleh et al 2022; Schneider & Lazzari 2022). Our discussion included illustrations of enzymes in fish feed (Figure 2) and an examination of how exogenous enzymes influence fish growth, as shown in Table 1.

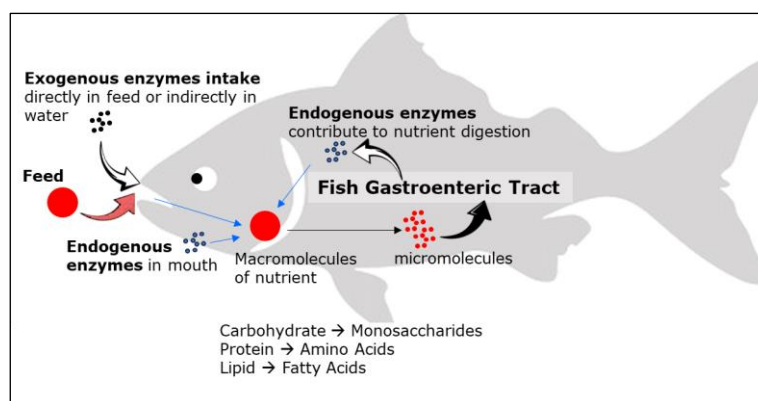


Figure 2. Role of enzyme in fish gastroenteric tract (original image).

Table 1

Enzymes use in fish feed, substrate, and their effect

<i>Enzyme (substrate)</i>	<i>Effect</i>	<i>References</i>
Proteases (proteins)	<ul style="list-style-type: none"> <li>• Proteases facilitate digestion by breaking down macromolecules into smaller particles like amino acids and peptides through hydrolysis.</li> <li>• Improvement of the function of endogenous enzymes secreted in small quantities, resulting in full nutrient digestion and improved nutrient absorption.</li> <li>• A remarkable effect on metabolic activity, feed conversion ratio (FCR), and weight gain (WG), decrease some anti-nutritional factors (ANFs).</li> <li>• Improved intestinal health and structure.</li> <li>• An increase in specific growth rate (SGR) and protein efficiency ratio.</li> <li>• Enhancement immune parameters in aquatic animals.</li> </ul>	Schneider & Lazzari (2022); Gopalraaj et al (2023)
Lipase (lipids)	<ul style="list-style-type: none"> <li>• Lipase breaks down lipids, by hydrolysis into fatty acids and glycerol, converting the insoluble fats into soluble form, so that they can be properly digested and assimilated.</li> </ul>	Bhilave (2019)

<i>Enzyme (substrate)</i>	<i>Effect</i>	<i>References</i>
	<ul style="list-style-type: none"> <li>• Lipase transformed into energy or material for growth.</li> </ul>	
Carbohydases (carbohydases)	<ul style="list-style-type: none"> <li>• Carbohydases include enzymes that degrade polymeric carbohydrates, reducing their molecular weight.</li> <li>• Carbohydase enhances mineral availability in diets.</li> <li>• Carbohydase improves gut health in animals consuming diets high in non-starch polysaccharides.</li> </ul>	Castillo & Gatlin III (2015)
Amylase (amylum)	<ul style="list-style-type: none"> <li>• Facilitate the breakdown of starch into simpler carbohydrates, such as glucose, maltose, and maltotriose.</li> </ul>	Gupta et al (2012); Mardani et al (2018)
Cellulase (cellulose)	<ul style="list-style-type: none"> <li>• Play crucial role to hydrolyse cellulose into simpler sugars.</li> </ul>	Ray et al (2007)
Hemicellulase (hemicellulose)	<ul style="list-style-type: none"> <li>• Degrade plant cell walls in feed.</li> </ul>	Sakamoto & Toyohara (2009)
Phytase (Phytates)	<ul style="list-style-type: none"> <li>• This enzyme catalyzes the release of orthophosphate groups from phytate, producing free inorganic phosphate and generating a cascade of lower inositol phosphates, including inositol pentaphosphate to monophosphate.</li> <li>• Improvement of phosphorus utilization from plant feedstuffs.</li> <li>• Enhance fish growth, nutrient utilization, and mineral absorption, reducing phosphorus waste and environmental impac.</li> <li>• Enhance intestinal histomorphology, hemato-biochemical performance and immune-oxidative indices, mitochondrial liver enzymes activities, lipid metabolism and returns, and improvement in terms of transcriptomic responses.</li> </ul>	Castillo & Gatlin III (2015); Kumar et al (2012); Negm et al (2024)

In principle, the use of exogenous feed enzymes has gained attention in aquaculture because such functional additives can improve nutrient digestion (Rodriguez et al 2021). Enzymes play a crucial role in fish digestion, breaking down large food molecules (macromolecules) into smaller, absorbable forms. This breakdown, achieved through hydrolysis, allows nutrients to be efficiently absorbed into the bloodstream. Specific enzymes, like carbohydases, lipases, and proteases, target carbohydrates, fats, and proteins, respectively, facilitating digestion and nutrient absorption into bloodstream. These micronutrients as product of enzyme digestion contribute to growth, development, and overall physiological function of fish (Furne et al 2005; Mata-Sotres et al 2016; Assan et al 2022; Amenyogbe et al 2024).

**Enzymes added for immunomodulatory effect.** Exogenous enzymes contribute to enhance immunological parameters or immune systems function, beside to improve fish growth performance, nutrient digestibility, intestinal topography and microbes, and water quality improvement (Farhangi & Carter 2007; Shi et al 2016; Ghodrati et al 2021; Gopalraaj et al 2023; Zhu et al 2025).

Enzymes are vital for the fish immune system, contributing to both innate and adaptive immunity (Ghalambor et al 2020). The innate immune system comprises physical barriers, cellular responses, and humoral components, such as lysozyme and the

complement system. Key immune cells in fish include macrophages, granulocytes, dendritic cells, natural killer (NK) cells, and cytotoxic T cells. Meanwhile, the adaptive immune system, which is based on B and T cells, is highly specific to a specific antigen (antigen receptors), and can provide long-standing immunity, including T cell receptors (TCRs), immunoglobulins (Igs) or antibodies, and major histocompatibility complex (MHC), are presumed to have occurred in the first jawed vertebrates (Dotta et al 2014; Romo et al 2016; Smith et al 2019; Mokhtar et al 2023).

One of the exogenous enzymes, namely lysozyme can be supplemented in fish feed to improve non-specific immunity, specific immunity response, and also bactericidal effect on gram-positive and gram-negative. Lysozyme supplementation can also significantly increase hematological indices such as white blood cells, red blood cells, and hematocrit of fish (Deng et al 2012; Shakoory et al 2018; Wu et al 2022; Aratboni et al 2024).

Lysozyme activity in fish blood serves as a valuable indicator of innate immune function (Montoya et al 2017; Amphan et al 2019; Biller et al 2021). Lysozyme is a vital enzyme in the innate immune system, providing robust defense against microbial pathogens, enhancing antibiotic efficacy, and supporting overall immune function (Ragland & Criss 2017; Primo et al 2018; Maryam et al 2024). Lysozyme is a crucial component of fish innate immunity, with lytic activity against a range of bacteria. It also has opsonic properties, activating phagocytes and the complement system. Lysozyme is present in multiple fish tissues and fluids, including mucus and plasma (Saurabh & Sahoo 2008). Lysozymes are hydrolytic enzymes that belong to the glycoside hydrolase family, known for cleaving  $\beta$ -(1,4)-glycosidic bonds in peptidoglycan, a key component of bacterial cell walls. This hydrolysis activity can hydrolyze the carbohydrate chains and compromises the integrity of the cell wall, causing the lysis of bacteria (Nawaz et al 2022). Lysozyme's antimicrobial effect involves breaking down bacterial cell walls by cleaving the glycosidic bonds between N-acetylmuramic acid (NAM) and N-acetylglucosamine (NAG) molecules (Skrzyniarz et al 2023). Thus, exogenous lysozyme supplementation can increase the availability of endogenous lysozyme in the fish body to protect its body from pathogenic microbes and disease.

In principle, supplementation exogenous enzyme to fish feed also improved health status and immunity of fish. Protease increase proteins and amino acids digestion and absorption, lipase increase lipids and fatty acids digestion and absorption, carbohydrase increase carbohydrates and monosaccharides digestion and absorption. The enzyme and metabolites enhance various hematological parameters, including red and white blood cell counts, hematocrit, and lymphocyte numbers, indicating improved immune function in fish. This suggests that exogenous supplementation can boost fish immunity, reduce inflammation, and promote overall fish health (Liang et al 2022).

Supplementation of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) protect the body from free radicals, especially reactive oxygen species (ROS). These enzymes protect against oxidative damage by breaking down reactive oxidative molecules eliminating surplus reactive oxygen radicals, minimizing self-inflicted harm, and enhancing cellular functionality. Furthermore, the antioxidant system protects fish from environmental stress (Hossain et al 2016; Abdel-Tawwab & Wafeek 2017; Aliko et al 2018; Hoseinifar et al 2020; Li et al 2022).

In addition, exogenous enzymes, those added to the diet or water for fish cultivation, not only influence the partitioning of nutrients to the host but also, through their action, support the growth of specific gut microbiota by providing nutrients (Bedford & Cowieson 2012). These enzymes not only influence how nutrients are distributed within the fish's body but also generate nutrients that certain gut bacteria can utilize. Exogenous enzyme supplementation as functional additives can indirectly influence gut microbes to produce their own enzymes. By breaking down complex nutrients, exogenous enzymes create more readily accessible substrates for gut bacteria. This can shift the microbial community, potentially favoring bacteria with the ability to utilize the resulting simpler compounds. This indicates the potential roles of exogenous enzyme as prebiotics to increase role of gut bacteria in breaking down nutrient into simpler forms to enhance nutrient digestion and also to improve gut microbe composition, including reducing the abundance of pathogenic microbes (Zheng et al 2019; Yang et al 2025).

**Enzyme's role in decomposing aquaculture waste.** Anthropogenic activities, or human activities, are the primary drivers of environmental contamination, leading to pollution of air, water, and soil, as well as habitat destruction. These impacts are widespread and can have severe consequences for ecosystems and human health (Ansari & Matondkar 2014; Arihilam & Arihilam 2019; Usman et al 2023).

Environmental pollution is escalating due to the reckless release of hazardous substances, posing significant threats to ecosystems and human health. Aquaculture activities are among potential sources of water pollution. In this environment, aquaculture activity produce waste that can be defined as the waste resulting from fish farming activities that caused deposits at the bottom or the water bodies. The primary cause of aquaculture wastes is the uneaten feed, fish feces, and other metabolism waste. Untreated discharge of these substances into water bodies can cause negative impact for fishes and aquatic ecosystem health (Lunda et al 2019; Galintin et al 2021; Chun et al 2024).

To mitigate this issue, remediation technologies have been developed, focusing on both organic and anorganic pollutants. Two primary approaches are employed: engineering-based methods, which rely on physical and chemical processes, and biological strategies, which utilize living organisms to restore environmental health. The use of enzymes may represent a good alternative for overcoming aquaculture waste. Enzymes possess several advantageous properties, serving as key catalysts in biological transformations with high specificity or broad applicability. They can extensively modify contaminants' structure and toxicity, often completely converting them into harmless anorganic compounds, thereby facilitating efficient chemical reactions.

Various methods have been developed to treat aquaculture wastewater and mitigate its environmental impact. Techniques like bioremediation, aeration, biocoagulation, and biofiltration can be applied in systems such as IMTA, RAS, and aquaponics to recover and recycle waste (Yusoff et al 2024).

Integrated multi-trophic aquaculture (IMTA) combines the cultivation of various aquatic species from different trophic levels. The byproducts of one species, like fish waste, are used as a resource for another, such as water plants absorbing nutrients. This approach mimics natural ecosystems and reduces waste by recycling nutrients (Azhar & Memiş 2023; Sharma et al 2025).

Recirculating aquaculture systems (RAS) enable water recycling and treatment, maintaining water quality independent of the supply water. Water is filtered and cleaned before being recirculated to the fish tanks, reducing water usage and waste. This allows for high-density culture of various fish species in a controlled environment (Ende et al 2024; Lal et al 2024).

Aquaponics integrates fish farming with soilless plant cultivation. The fish waste serves as nutrients for the plants, which in turn filter the water for the fish, forming a self-sustaining cycle. This system reduces the need for external fertilizers and can be a sustainable method for food production (Stoyanova et al 2024; Nair et al 2025).

In principle, these methods play a role in aquaculture waste recycling which involves transforming waste products from fish farming into valuable resources and minimizing environmental impact. Enzymes are one of important decontaminating agents (Rao et al 2010). Exogenous enzyme directly or in collaboration with endogenous enzyme from bacteria can remediate the pollutant agent in remediation mechanisms. Enzymatic remediation occurs in two stages: phase I, where contaminants are modified through oxidation, reduction, and hydrolysis, increasing their solubility, and phase II, where conjugation reactions reduce toxicity or detoxification (Chia et al 2024).

The supplementation of exogenous enzymes can increase the decomposition of organic contaminants in aquaculture environments. Exogenous enzymes, like proteases lipases, etc. enhance the digestion and utilization of nutrients, leading to a reduction in unutilized feed and subsequent organic matter buildup.

According to Kurniawan et al (2023), bio-enzymes or eco-enzymes derived from fruit waste contain diverse microorganisms, including beneficial fungi and bacteria. The organic compounds in these bio-enzymes serve as nutrients for the microbes, enabling them to function as synbiotics. Although the term synbiotic typically refers to probiotic-

prebiotic combinations, bio-enzymes can be considered synbiotic due to their microbial communities and nutrient-rich composition, which benefits the host similarly.

The addition of exogenous enzymes such as bio-enzymes or eco-enzymes can play a role as synbiotics. It can boost bioremediation's effectiveness in aquaculture by leveraging microbes to degrade organic waste, recycle nutrients, and improve water quality. By minimizing antibiotic use, bioremediation promotes ecological health and reduces health risks for consumers, while probiotic bioremediators protect cultured organisms from infectious diseases (Devaraja et al 2002; Sha et al 2022; Sun et al 2022).

Additionally, enzymes possess chemical or functional bonds that enable them to bind contaminant ions in the environment. Enzymes can indeed bind to contaminants, including metal ions, in the environment due to specific chemical or functional bonds within their structure (Robinson 2015; Wang et al 2023).

Enzymes behave like proteins, amphoteric biopolymers (Yang et al 2016), meaning enzyme can act as either acids or bases depending on their surroundings. This property arises from the presence of acidic groups (carboxyl,  $-\text{COOH}$ ) and basic groups (amino,  $-\text{NH}_2$ ) (Wiltgen 2009; Takahashi 2013), allowing enzymes to react with both acids and bases. In acidic environments, the amino group ( $-\text{NH}_2$ ) can accept protons ( $\text{H}^+$ ), causing the enzyme to become cationic or positively charged. Conversely, in basic environments, the carboxyl group ( $-\text{COOH}$ ) can release protons ( $\text{H}^+$ ), resulting in the enzyme becoming anionic or negatively charged (Weiss 2007).

Proteins or enzymes are amphoteric due to their amino acid composition, which features balanced positive and negative charges, resulting in a net neutral charge. This is attributed to the presence of zwitter ions, also known as dipolar ions, that contain both cations and anions within a single molecule (Yamazaki et al 2010; Kurinomaru et al 2014; Dinic et al 2022).

We classified two contaminant components from aquaculture waste, namely organic matter and anorganic matter. The addition of enzymes to the environment can be responsible for reducing contamination of organic and inorganic materials. Enzymes play a role in neutralizing pollutants by balancing anions and cations, facilitating the removal of organic and anorganic contaminants. We illustrated the role of enzyme in reducing contaminant in the environment (Figure 3). Figure 3 showed that enzymes play a crucial role in decomposing aquaculture waste, offering a sustainable solution for waste management and resource recovery. They can break down organic matter, reduce pollutants, and potentially even yield valuable byproducts, and anorganic contamination, including metals, from the environment (Costa et al 2016; Khiari 2024; Zheng et al 2024). Kurniawan et al (2023) revealed that the presence of organic matter, including hydrolitic enzyme can impact the decrease of heavy metal contamination and the increase of pH values in acidic waters. The organic matter is decomposed by exogenous hydrolitic enzyme or endogenous from microbes to produce ions that can bind  $\text{H}^+$  cations and heavy metals. This mechanism impacts heavy metals toxicity reduction or detoxification and also increases the pH value.

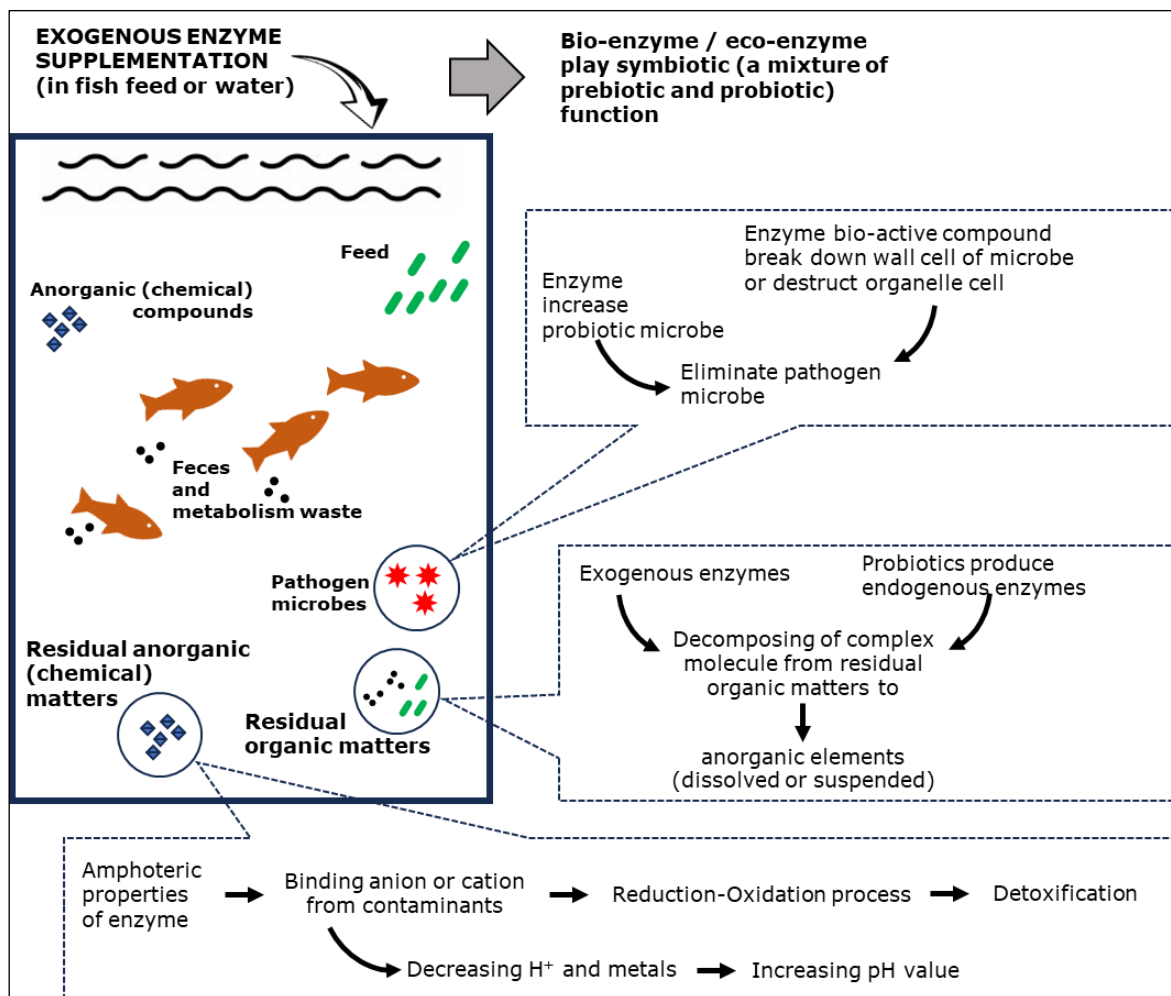


Figure 3. The role of enzymes on aquaculture environment (original image).

**Conclusions.** Enzymes are valuable tools in aquaculture production, particularly for enhancing nutrient absorption and managing waste. They break down large food molecules into smaller, more readily absorbable forms, improving fish digestion and nutrient utilization. Additionally, some enzymes can help manage waste by breaking down organic matter and improving water quality. Enzymes derived from organic matter like fruits and vegetables, often referred to as eco-enzymes or bio-enzymes, can be used in a synbiotic context, which refers to a mixture of probiotics and prebiotics that confer beneficial effects on the host, enhancing growth performance and health. In aquaculture environment, enzymes can target specific pollutants, ensuring efficient and targeted removal of contaminants. Enzymes were natural catalysts that accelerate chemical reactions, including decomposition or degradation of organic matter, the breakdown of pollutants and detoxification. Exogenous enzymes, introduced into the environment from outside of microorganisms, can enhance the effectiveness of microbes in degrading pollutants by stimulating the production of endogenous enzymes. It contributed to a more efficient degradation or detoxification of contaminants through both decomposition and detoxification mechanisms and also water quality improvement.

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**Conflict of interest.** The authors declare that there is no conflict of interest.

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