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New frontiers in the use of biotics in aquaculture: Towards advanced strategies beyond live microbial cultures

Nuevas fronteras en el uso de bióticos en la acuicultura: Hacia estrategias avanzadas más allá de los cultivos microbianos vivos

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The intensification of aquaculture, driven by market demand, necessitates strategies to maintain environmental health and ensure the industry's sustainability. In this context, the success of aquaculture operations is closely linked to feed costs and quality, and profitability depends directly on feed efficiency, growth rate, and pathogen resistance (Pepi & Focardi, 2021). However, intensification increases the risk of infectious disease outbreaks, which represents a significant constraint on sustainable industry growth. Consequently, there is urgent pressure to reduce antibiotic use in intensive systems, as excessive use contributes to the emergence of resistant bacterial strains and to undesirable levels of environmental residues (Lulijwa *et al.*, 2020). Under these circumstances, probiotics have emerged as a key strategy for preventing certain bacterial diseases in fish.

Probiotics are defined as viable microbial supplements that, when administered in adequate amounts, confer beneficial effects on aquatic organisms, including improved growth, increased survival, enhanced stress tolerance, promotion of reproduction, and inhibition of pathogen proliferation (Martínez-Cruz *et al.*, 2012). Diverse mechanisms mediate these effects, such as competitive exclusion, in which the probiotic interferes with pathogens by directly competing for adhesion sites in the digestive tract and for essential nutrients. In addition, probiotics exert antagonism by producing inhibitory compounds, such as bacteriocins, siderophores, and organic acids, thereby altering pH and creating a hostile environment for pathogens. A predominant mechanism is immunomodulation, in which probiotics stimulate the host's non-specific cellular and humoral immune responses. Probiotics also contribute nutritionally by improving feed digestibility through the production of enzymes such as amylases and proteases, or by synthesizing essential nutrients, including vitamins and fatty acids. Representative genera used in aquaculture include *Bacillus, Lactobacillus*, *Carnobacterium*, *Vibrio*, *Pseudomonas*, *Shewanell*a, and *Saccharomyces* (Newaj-Fyzul *et al*., 2013). Given the need to maintain the viability of probiotic microorganisms throughout production, storage, and delivery to the intestinal tract, the development of "next-generation" products such as parabiotics and postbiotics has gained momentum.

Parabiotics represent an advanced strategy in aquaculture biotechnology. They are defined as the use of inactivated (non-viable) microbial cells or their subcellular fragments, administered in the diet, that confer benefits on the host without requiring viability. This characteristic is their main operational advantage, as it simplifies production, storage, and handling. Formalin or heat treatment often inactivates cells (heat-killed, HK), and the functional components may include cell-wall proteins or whole-cell proteins (Wisastra *et al*., 2025). Evidence in aquaculture demonstrates that these stable products elicit significant beneficial responses. For example, the use of heat-killed cells improves digestive enzyme activity and promotes weight gain in particular amphibian and crustacean species. Researchers have used fragments of probiotic cell walls to enhance the immune response in freshwater fish. Likewise, the use of inactivated probiotic cells increases survival rates and improves resistance to bacterial diseases in various freshwater and marine fish species.

Postbiotics, in turn, refer to soluble factors and bioactive metabolites secreted by live microorganisms or released upon cell lysis. These molecular components include lipoteichoic acids, exopolysaccharides (EPS), bacteriocins, peptides, organic acids, short-chain fatty acids (SCFA), and cell-free extracts (Kumar *et al.,* 2024). The use of postbiotics has proven to be a powerful tool for modulating metabolism and immune responses in aquatic species. For instance, SCFA can increase antioxidant capacity in particular fish species. In contrast, organic acids and lipoteichoic acids have shown mitigating effects by alleviating enteritis and intestinal inflammation in some marine species, and bacteriocins have increased survival rates in crustaceans.

To unlock the full potential of postbiotics and parabiotics in the aquaculture industry, we must overcome several challenges. First, their application remains limited relative to that of probiotics, underscoring the need to expand research on their use in aquaculture production systems. Furthermore, it is essential to advance the characterization and standardization of their bioactive components. The composition and functionality of postbiotics depend directly on the culture conditions of the producing microorganisms; therefore, to achieve their full industrial potential, rigorous analytical protocols are required to ensure product consistency and reproducibility.

The future of disease prevention in intensive aquaculture will depend on the capacity to isolate, characterize, and accurately apply these functional molecules to mitigate the high costs associated with feed by providing biologically efficient, stable, and scientifically substantiated health solutions.

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