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Probiotics as a sustainable alternative to antibiotics in aquaculture: a review of the current state of knowledge

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ABSTRACT

Aquaculture, a fast-expanding international business, is severely impacted by disease outbreaks, water quality issues, and the misuse of antibiotics, which promote antimicrobial resistance. These problems result from the buildup of organic matter, including dead organisms, feces, and excess feed, which releases toxic gases like hydrogen sulfide and ammonia. Conventional methods of controlling diseases through the use of antibiotics and synthetic chemicals are ineffective at large scale and cause environmental as well as health problems. Natural substitutes such as immunostimulants, herbal extracts, and prebiotics have therefore been investigated; however, many of these have conflicting outcomes or do not address more general environmental issues. Probiotics or useful microbes have come forward as environment-friendly and sustainable options. Probiotics stimulate immune reactions, decrease pathogenic loads, enhance digestion, and enhance water quality. In contrast to single-mode use of antibiotics, the action of probiotics is multifarious in nature such as competitive exclusion, immunomodulation, and synthesis of antimicrobial compounds. In aquaculture systems, they are essential for preserving a balanced microbial environment, lowering pathogens, boosting immunity, and fostering the development and well-being of cultured species. Through a variety of strategies, such as immunomodulation, competitive inhibition, and environmental modification, probiotics provide these advantages. Probiotics provide long-term, multifaceted solutions that enhance aquatic organisms' health and their rearing habitats, in contrast to unilateral disease control techniques. The current challenges in aquaculture, processes of antibiotic resistance, and the multifunctional functions of probiotics are the topics of discussion in this review. The review also incorporates recent evidence, such as combinations with herbal drugs and nanoparticles, species-specific use, and delivery methods. Hints for future directions in research are given to enable probiotics to enhance sustainable aquaculture further.

Introduction

Aquaculture is the farming of aquatic animals like fish and shellfish that are of economic importance. This practice improves conditions to produce food that is rich in protein and is easily available. Unlike traditional fishing, aquaculture dramatically increases the supply of seafood that is available for human consumption (Iheanacho et al., 2025). Due to the increasing exploitation of the populations of wild fish, aquaculture has become a vital industry across the globe. The UN's World Population Prospects (2022) estimates that by 2050, the global population will reach 9.7 billion people, with Asia growing the most (United Nations, 2022). The FAO also expects that aquaculture will help to address the demand and supply gap of fish. With the limits of supply of wild fish, many countries especially in Asia are focusing on aquaculture in order to boost em economy as traditional farming is unable to keep pace with population growth (Msangi et al., 2013).

Compared to 30.6 % in 2003, the percentage share of aquaculture in worldwide fisheries production has gradually increased to 46 % in recent years. As of 2023, global aquaculture production is estimated to surpass 100 million tons (live weight), valued at approximately USD 180 billion. The FAO database contains 600 species of fish that are cultivated in freshwater, seawater, and brackish water bodies (Paruğ et al., 2024).

Asia continues to lead globally in aquaculture output, especially in shrimp cultivation, which comprises over 80 % of the world's farmed shrimp. 90 % of edible crustacean production comes from Asian countries for the 15 species of crustaceans—marine, brackish water, and

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freshwater—that are cultivated across different Asian countries (Bhujel, 2024).

The increase in the intensity of production and international seafood trade has been the main catalyst for advancements in aquaculture (Blanchard et al., 2017). On the other hand, modern aquaculture practices, which use high stocking densities, exacerbate stress for the cultured animals. These highly stressful situations often lead to disease outbreaks and ecological problems, incurring significant economic damage (Araujo et al., 2022).

This review is an all-encompassing summary of probiotic application in aquaculture. It includes the limitations of the use of antibiotics, mode of action of probiotics, strain-specific effects, delivery systems, and synergistic approaches with herbs and nanoparticles. This article also suggests future directions in exploring further the application of probiotics in aquatic ecosystems.

Literature Search Strategy and Inclusion Criteria

To guarantee a thorough and current review, we searched the literature via databases like PubMed, Scopus, and Web of Science. Search terms employed were: "probiotics", "aquaculture", "antibiotic resistance", "fish health", and "sustainable aquaculture". Publications between 2000 and 2025 were included. Peer-reviewed review and research articles that applied to aquaculture practices, probiotic action, and health/environmental effects were included.

Problem associated with antibiotics use in aquaculture

Use of antimicrobials in aquaculture

The intensification of aquaculture has been associated with enhanced prevalence of bacterial diseases and the subsequent increased use of antibiotics. The antibiotics are utilized for therapeutic, prophylactic, and metaphylactic applications and are usually delivered through medicated feed or addition into the water column. Though successful in the short run, this practice has major pitfalls, such as contamination of the environment, accumulation of residues, and the emergence of antimicrobial resistance (AMR) (Weldon & Hoffman, 2023). Antibiotic usage differs considerably between regions. For instance, Norway applies some 1 g of antibiotics to each metric ton of fish produced, while in Vietnam it may be more than 700 g per ton. Shrimp cultivation within Southeast Asia has also been linked to extensive antibiotic use, frequently without rigorous control (Mukhtar et al., 2025).

Excessive use of antibiotics not only undermines the efficacy of treatment but also upsets microbial balance in aquatic ecosystems, rendering fish vulnerable to opportunistic infection (Asif et al., 2024). Furthermore, most antibiotics are relatively poorly absorbed by aquatic animals—specifically shrimp—resulting in their accumulation in water and sediment and hence in increased environmental toxicity (Kümmerer, 2009).

To address such issues, aquaculture, in particular, has increasingly turned to chemical options and veterinary pharmaceuticals. Nevertheless, the raising concerns of the long-term use of antimicrobial substances, especially in regard to the persistence and dissemination of resistant antibiotic genes, remains a problem (Jian et al., 2021).

The Petersen noted that the intensification of fish farming has contributed to the emergence of bacterial diseases, which, in turn, has increased the use of antimicrobials (Petersen, et al., 2002). Moreover, Henriksson directs attention towards the mentioned disparities and claims that due to differences in regulatory policies and coverage in various countries, it is nearly impossible to assess the total estimate of antibiotics used in aquaculture (Henriksson et al., 2018). Stephen underlined antibiotics use differences where some countries minimally used them and others heavily relied on them. During the mid-1900s, it was reported that shrimp aquaculture in Thailand had a rough estimate of around 500–600 metric tons of antibiotics in use. It is worth noting that the volume of antibiotics applied in aquaculture varies remarkably: from as little as one gram per metric ton of fish produced in Norway to 700 g per metric ton in Vietnam (Stephen et al., 2023).

Therapeutic use – treating existing infections

Metaphylactic Use – Taking care of an infected person while controlling the transmission of infection.

Prophylactic Use - Putting measures in place to control infection spread beforehand (Thitamadee et al., 2016)

Antibiotics are typically incorporated into the feed and are given to fishes kept in common tanks or cages. They are, however, poorly metabolized by the shrimp, resulting in the release of unnecessary antibiotics into the surrounding water, thereby exacerbating environmental concerns (Tran et al., 2025).

In contrast to land-based farming of animals, aquaculture involves the use of antibiotics which is done by pouring them into the water or mixing them with feed. This action applies selective pressure that encourages bacteria to become resistant (Done et al.,2015).

Bacteria develop resistance through two primary mechanisms:

1. Intrinsic Resistance - These includes some sort of bacteria that lacks natural defenses to certain antibiotics due to its inability to take in the drug, absence of receptors to the target or missing important parts of the cell needed for the antibiotic to act on.
2. Acquired Resistance - Formerly sensitive bacteria can become resistant either because chances are created through changing pathways due to random changes in genetic structures or because of receiving resistance parts from others through horizontal gene transfer (Lerminiaux & Cameron, 2019).

The three main ways this occurs include:

Transformation – Bacteria take in and keep separate DNA from the

Transduction – Viruses convey resistance genes among bacteria.

Conjugation – Bacteria exchange genetic material directly through cell-to-cell contact.

Current research underscores the requirement for alternatives to traditional antibiotics in aquaculture. Probiotics, prebiotics, and synbiotics have been considered to possess potential in minimizing pathogenic load and enhancing disease resistance without adding to antimicrobial resistance (Abdel-Latif et al., 2022; Yilmaz et al., 2022).

Disease challenges in aquaculture

According to De Bruijn et al. (2018), diseases in aquaculture result from the interplay of four factors, which are the species of the host, the environment, the system's surrounding, and the microorganisms in it. Most of the time change in the water's temperature, salinity, or even nutrition content will trigger an outbreak (Chengula et al., 2024). An imbalance of pathogenic and beneficial microbes is proposed to markedly influence disease emergence, especially in shrimp farming (Xiong et al., 2024).

Innovative feeding techniques have significantly improved aquaculture productivity. Many fish and shrimp feed manufacturers now include additives to enhance growth and profitability (Sarker, 2023). However, excessive antibiotic use over the last 60 years has led to strong selection pressures that encourage bacterial resistance (Pepi & Focardi, 2021).

Certain bacteria, particularly *Vibrio* species, can acquire antibiotic resistance genes through plasmids. These genes spread via plasmid transfer, bacteriophage-mediated transduction, or absorption of free-floating genetic material from water or sediments (Motlagh, 2016).

Probiotics as an alternative to antibiotics

Probiotics—live microorganisms that, when administered in sufficient quantities, provide health benefits to the host—are a potential substitute for antibiotics used in aquaculture systems (Amenyogbe et al., 2020). These microorganisms, such as Lactobacillus, Bacillus, Enterococcus, and Saccharomyces species, serve a broad range of functions in promoting fish and shrimp health (Butt et al., 2021). Beneficial microorganisms called probiotics provide an environmentally friendly way to lessen aquaculture's reliance on antibiotics (Amenyogbe et al., 2023). Probiotics help aquatic species' immune systems, digestion, feed efficiency, and general health (Aneeet al.,2021).

Among their advantages are:

- Fighting off dangerous bacteria to stop infections.
- Producing vital vitamins and fatty acids.
- Improving digestion and nutrient absorption.
- Boosting the immune system.
- Balancing microbial populations to improve water quality (Wang et al., 2020).

Effectiveness and mechanism of probiotics

Since the middle of the 1980s, probiotics have been utilized with success in aquaculture (Austin & Sharifuzzaman, 2022). Their capacity to boost immune function, promote good gut flora, and stop disease outbreaks accounts for their efficacy (Banerjee & Ray, 2017).

Additionally, probiotics

Improve gut health by producing antimicrobial compounds like bacteriocins, lysozyme, and organic acids that prevent the growth of pathogens.

Stabilize intestinal microbiota to improve gut health; lessen health problems associated with stress; and increase the host's resistance to the negative effects of heavy metals. (Feng, Wang, 2020).

Algae, yeasts, and bacteria are common probiotic sources in aquaculture (Hai, 2015).

Probiotics should be chosen according to their compatibility with host species and given at the right dosages in order to optimize their benefits (Fenster et al., 2019).

Probiotics thus support fish health, productivity, and environmental safety in aquaculture by offering a viable and efficient substitute for antibiotics.

Potential benefits of probiotic in aquaculture

Application of probiotics as growth promoters in aquaculture

Probiotics provide notably multiple benefits aside from mere disease prevention. Promoting an ample and balanced growth of organisms alike, probiotics improve feed efficiency, confer better immunity to organisms, stabilize water quality, such that a minimum quantity of antibiotics is required (Anee et al., 2021). These amenities match the need for sustainable, environment-friendly methods of aquaculture that support animal welfare and consumer safety for the humans (Amenyogbe, 2023). Probiotics can curb chemical pollution in aquatic systems, thus restoring the ecological balance. Having fewer side effects when compared to conventional chemotherapeutics, probiotics lose their environmental persistence and bacteria develop resistance against the drug (Feng et al., 2018).

Fish are always interacting with their surroundings, and microbial communities have a big influence on how well they absorb nutrients and how resistant they are to disease (Chen et al., 2022). According to Nayak et al. (2010), probiotic supplementation is essential for preserving microbial balance, encouraging growth, and strengthening fish immune responses.

According to recent studies, Staphylococcus edaphicus effectively increases the immune response of Kelabau fish (Osteochilus melanopleurus), improving blood parameters and survival rates after exposure to Pseudomonas and Aeromonas hydrophila (Agustina et al., 2018). Additionally, without showing any harmful effects, Staphylococcus sp. Strain JC20 has shown cellulolytic qualities and probiotic potential in red tilapia (HAKKINEN et al., 2025).

Table 1
Common Probiotic Strains.

Probiotic Strain	Host Species	Benefits	References
Bacillus subtilis	Tilapia, Shrimp	Growth, immunity, water quality	Monier et al., 2023 Liu et al.
Lactobacillus plantarum	Carp, Tilapia	Antibacterial, antioxidant	Ahmadifar et al., 2019
Enterococcus faecium	Shrimp	Competitive exclusion	Knipe et al. 2021
Saccharomyces cerevisiae	Tilapia	Immune stimulation	He et al. 2009
Pediococcus acidilactici	Shrimp	Ammonia reduction	Wu et al. 2022

Probiotics offer a sustainable alternative for disease prevention, especially in the management of red spot disease, given the growing concerns about antibiotic resistance. Their ability to modulate immune functions and inhibit pathogenic bacteria supports healthier fish populations while reducing reliance on antibiotics in aquaculture (Wang et al., 2023).

Probiotics in stress reduction and disease prevention

Fish health and well-being are adversely affected by environmental changes and stress management (Amenyogbe et al., 2024). The effects of probiotics on fish stress responses are still being investigated. It has been demonstrated that these advantageous bacteria, which are well known for their function in immunity and gut health, increase stress resilience in fish exposed to environmental stressors (Fachri et al., 2024).Probiotics greatly enhance stress tolerance by stabilizing the gut microbiota, which is linked to stress-related physiological and behavioral changes in fish (Kiran et al., 2024).

According to research, some probiotic strains improve stress tolerance by controlling the levels of stress hormones, especially cortisol, through the hypothalamic-pituitary-interrenal (HPI) axis (Ciji & Akhtar, 2021). It has been discovered that probiotics affect this endocrine system, encouraging a more balanced reaction to stress (Dinan & Cryan, 2012). Furthermore, certain probiotic strains improve gut-brain connections, which lowers cortisol levels and inhibits the activation of the HPI axis under stress (Lee et al., 2024). Additionally, probiotics improve gut health and immune responses, which together help reduce inflammation, enhance nutrient absorption, and prevent immunosuppression brought on by stress (Fachri et al., 2024).

Probiotics and Para probiotics are being studied further, and the results show promise in lowering parasitic, viral, and bacterial infections in aquaculture. By enhancing gut microbiota and fortifying immune defenses, dietary probiotic supplements have been demonstrated to dramatically reduce bacterial infections (Cunningham-Rundles et al., 2011). Furthermore, some probiotic strains make parasites uncomfortable, which lowers infestation rates and improves fish health in general (Assefa & Abunna, 2018).

Finding the best probiotic strains, maximizing dosage amounts, and choosing appropriate application techniques should be the main goals of future studies (Hathi et al., 2021).Probiotics must be tested under a variety of circumstances, including temperature changes, pollutants, and handling stress, in order to guarantee their wide applicability, considering the variety of environmental stressors (Amenyogbe et al., 2024). Probiotics' capacity to improve fish health and reduce stress offers a significant chance for sustainable fisheries, aquaculture, and conservation (Sihag & Sharma, 2012).

Table 2
Key Mechanisms of Probiotic Action in Aquatic Species.

Mechanism	Description	Example Strains	
Competitive exclusion	Blocks adhesion of pathogens via competition for nutrients/sites	*L. pentosus, E. faecium*	Nayak (2010)
Antimicrobial production	Secretion of bacteriocins, organic acids, enzymes	*B. subtilis, L. plantarum*	Dong et al. (2020), Rocchetti et al., 2021
Immune system modulation	Stimulates cytokine production and phagocytic activity	*B. subtilis, Lactobacillus* spp.	Nayak (2010), Dong et al. (2020)
Antioxidant enhancement	Increases enzymes like SOD, CAT, GPx	*Lactobacillus plantarum*	Hoseinifar et al. (2020), Rocchetti et al. (2021)
Water quality improvement	Degrades organic waste, reduces ammonia/nitrite	*B. cereus, P. acidilactici*	Cranford et al. (2022), Nafees et al. (2022)

Probiotics as an eco-friendly approach to water quality management

By decomposing organic waste and harmful substances, probiotics help aquaculture systems maintain water quality (Manam, 2023). By breaking down fish waste, leftover food, and other organic waste, these helpful bacteria help maintain a healthy aquatic environment by producing carbon dioxide, nitrate, and phosphate (Mallik et al., 2024).

According to studies, mixed Bacillus probiotics dramatically enhance water quality during white shrimp cultivation by stabilizing pH and lowering dangerous ammonia and nitrite levels (Nimrat et al., 2020). In shrimp farming, adding Bacillus subtilis at a concentration of 10^{10} CFU/ml has been successful in reducing total ammonia levels and enhancing water quality overall (Kewacharuen and Srisapoome, 2019).

Similarly, the application of *Bacillus cereus* and *Pediococcus acidilactici* at the same concentration has been reported to decrease nitrate, ammonia, and biological oxygen demand in pond water (Hassan et al., 2022).

Probiotics and immune system enhancement in aquatic animals

Probiotic supplementation strengthens the immune system of aquatic species, increasing their ability to resist bacterial infections. Probiotics improve non-specific immune responses, increasing disease resistance, according to a number of studies (Liu et al., 2014). Fish immunity is further strengthened by probiotics, which also increase the production of immunoglobulins and stimulate important immune cells like neutrophils, monocytes, and macrophages (Nayak et al., 2010).

Probiotics derived from Bacillus and Vibrio species have been demonstrated to improve resistance to Vibrio harveyi and white spot syndrome in shrimp farming (Kewcharoen & Srisapoome, 2019). Furthermore, adding Lactobacillus plantarum to shrimp diets enhanced the expression of immune genes and antioxidant enzyme activity (Zheng et al., 2017). Similarly, in groupers (Epinephelus coioides), Bacillus subtilis has been shown to improve respiratory bursts, phagocytosis, and complement activity, all of which increase disease resistance (Dos Santos, 2022).

They enhance phagocytosis, a primary defence mechanism, although research on their impact on respiratory burst activity has yielded mixed results (Biller & Takahashi, 2018).

Moreover, probiotics contribute to antioxidant defences by increasing superoxide dismutase (SOD), catalase, and glutathione peroxidase levels while reducing tissue damage markers such as ALT and AST (Hoseinifar et al.,2020).

Probiotic supplementation enhances immune function, gut health, and hybrid grouper growth, according to recent studies. Bacillus Spp supplementation increased weight gain and upregulated immune-related genes, such as TNF-α and IL-1β, according to research by Dong et al. (2020). The strongest immune response was seen in fish fed Bacillus subtilis, indicating that probiotics made from fish intestines greatly improve disease resistance in aquaculture (Liu et al., 2017).

Mechanisms of probiotic in aquaculture

Competition for adhesion sites

Through a process called "competitive exclusion," probiotics compete with pathogens for adhesion sites and nutrients, preventing them from adhering to the gut lining. Because it aids in the colonization of the gut by beneficial microbes and inhibits the adherence of pathogens, this mechanism is crucial for the selection of probiotics (Collado et al. 2010). It has been shown that Enterococcus fecium and Lactobacillus pentosus can adhere to the intestinal mucus layer of shrimp, which allows them to compete with pathogens like Vibrio spp. (Du et al., 2022).

According to recent research, heat-killed Lactobacillus plantarum, a paraprobiotic, can stick to intestinal mucus and possibly prevent fish pathogen attachment sites (Bernardeau & Vernoux, 2024). Additionally, the yeast *Saccharomyces cerevis*iae has been reported to reduce *Aeromonas hydrophila* colonization in Nile tilapia (Iwashita et al., 2015). Using probiotics that contain multiple strain altrnatives especially in different aquaculture Spicies. This enhanced competitive exclusion supports better health and microbial balance in aquatic environment (Dias et al., 2022).

Production of inhibitory compounds

Both Gram-positive and Gram-negative bacteria are inhibited by the antimicrobial compounds produced by probiotic bacteria. These aid in the suppression of pathogenic microorganisms and include bacteriocins, hydrogen peroxide, lysozymes, proteases, and siderophores (Zorriehzahra et al., 2016). Furthermore, probiotics generate organic acids that lower gut pH and prevent the growth of pathogens, including lactic, acetic, butyric, and propionic acids (Dittoe et al., 2018).

Heat-killed Lactobacillus plantarum is a promising probiotic that limits pathogen colonization in fish by producing inhibitory substances, according to recent research (Rocchetti et al., 2021).

Antimicrobial properties

Numerous probiotics have antibacterial qualities that protect against common fish pathogens. Compared to single-strain probiotics, multi-strain probiotic formulations have shown a greater inhibitory effect against pathogens (Puvanasundram et al., 2022). It has been discovered that Lactococcus lactis exhibits antibacterial action against Aeromonas hydrophila in tilapia. (Zhou et al., 2010).

Probiotics contribute to improved water quality, enhanced stress tolerance, and immune system activation in aquatic organisms (Dash et al., 2018).

Antifungal action

Saprolegniosis and other fungal infections pose a serious threat to aquaculture. Probiotics are becoming a more viable biocontrol strategy for avoiding fungal infections in aquaculture, even though chemical antifungal treatments are still available (Lindholm-Lehto, Pylkkö 2024).

Techniques for delivering probiotics in aquaculture

A variety of techniques, such as injection, bathing, live food, artificial diets, and direct addition to culture water, can be used to introduce probiotics to aquatic organisms.

Table 3
Delivery Methods for Probiotic Strains.

Method	Description	Suitability	References
Water application	Direct to water	Larvae, pond control	Hassan et al. 2022
Live feed enrichment	Enriched *Artemia*, rotifers	Early larvae	Nielsen, 2021
Microencapsulation	Coated with alginate/chitosan	All stages	Vijayaram et al. 2024
Bath/Immersion	Immersion in probiotic solutions	Fry, broodstock	Beça, 2017
Injection	Direct injection	Broodstock, research	Vine et al., 2006

Injection technique

A saline solution containing probiotics is injected into the aquatic host. However, this method is not practical for small or larval fish due to the need for expert handling and time consumption (Vine, 2004).

Bathing method

The probiotic is cultured in a broth medium and diluted with sterile water. After being submerged in this solution, the host is returned to its tank. Another strategy is to add the probiotic straight to the tank, where the host will naturally absorb it (Verschuere et al., 2000).

Artificial diet

Prepared diets that contain vital nutrients are supplemented with probiotics. However, because fish larvae's digestive systems are still developing, this approach is inappropriate for them (Pramanick et al., 2019).

Addition to culture water

By lowering dangerous pathogens, probiotics can enhance the quality of water. Fish kept in open-sea cages cannot use this technique, but it works especially well for live feed (Can et al., 2023).

Live food

One of the best methods for delivering probiotics is through live food. Artemia, copepods, rotifers, and microalgae are examples of common live food sources. These organisms not only enhance the host's nutrition but also prevent pathogen growth (Sanders & Marco, 2010).

Advantages and future perspectives

By supporting fish health and preventing illness without escalating antibiotic resistance, probiotics provide an alternative to antibiotics. Certain probiotics function by generating antimicrobial compounds or by competing for nutrients with pathogens (Sihag & Sharma, 2012). According to research, probiotics such as Bacillus sp. help prevent the growth of pathogens by reducing the availability of iron, which is necessary for the growth of many dangerous bacteria (Sihag & Sharma, 2012).

Probiotics can be taken either by themselves or in conjunction with other healthy substances. Research indicates that combining different probiotics enhances immune responses and survival rates in a range of fish species (Nayak et al., 2010). Fish metabolism may be adversely affected by excessive probiotic supplementation, so dosage is crucial (Naiel et al., 2022).

Probiotics have the potential to improve fish health, water quality, and overall aquaculture productivity.

Future perspectives

Despite bright results, certain challenges persist

- ➢ Strain specificity: Probiotic effects vary with the species considered and the context; hence, a careful selection procedure should be followed in the choice of strains (Arora & Baldi, 2017).
- ➢ Standardization and formulation: Determination of dosage, formulation stability, and shelf life bundle great importance (Ahmed et al., 2024).
- ➢ Combination therapies: Future studies should evaluate synergistic activity of probiotics with prebiotics, herbal extracts, and nanoparticles (Vijayaram et al., 2024).
- ➢ Long-term field trials: The laboratory success needs to be validated thus through commercial-scale trials conducted at multiple locations under differing environmental conditions (Grumet et al., 2020).
- ➢ Regulatory frameworks: To ensure the safe and effective use of probiotics in various aquaculture systems, there needs to be a harmonized regulatory set of guidelines across nations (Arora & Baldi, 2017).

It is expected that newly emerging technologies such as genomics, metabolomics, and nanobiotechnology will greatly help in the identification of novel strains and enhancing probiotic efficacy.

Conclusion

A viable and long-term strategy for preventing illness and promoting growth in aquaculture is the use of marine probiotics in place of antibiotics. Probiotics support a balanced microbial ecosystem, boost immune responses, and improve nutrient absorption in farmed species, in contrast to antibiotics, which cause antimicrobial resistance and disturb aquatic microbiota. Probiotics minimize the need for chemical treatments by reducing pathogen colonization naturally through the promotion of beneficial bacteria. In addition to ensuring healthier aquatic stocks, this change satisfies consumer and environmental demands for seafood free of residue. Even though there are still issues with strain selection, dosage optimization, and environmental fluctuations, probiotics will become more effective as long as research and practical use continue to progress. For aquaculture to be sustainable, ethical, and financially successful, switching from antibiotics to probiotics is not merely a choice—it is a requirement.

The development of probiotics for use in aquaculture now represents a paradigm shift in the preventive management of health in water organisms and hence ecological sustainability. Practically speaking, probiotics counteract these problems posed by antibiotics by working competitively with pathogens, by boosting immunity or tolerance during stress, or by improving water quality. Given the increasing global awareness of the problem of microbial resistance, the good-time specialist on probiotics stands as a natural practical alternative and an alternative that has promise.

Will multidisciplinary research, policies that support them to build a strategic environment, and industry-based collaboration now allow the transformation of aquaculture systems into being a relatively resilient, productive, and sustainable sector?

CRediT authorship contribution statement

Khushbu khapandi: Investigation, Data curation. **Sanjana Katariya:** Formal analysis, Conceptualization. **Anjali Gadhiya:** Methodology, Investigation. **Deviben Chhatrodiya:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial

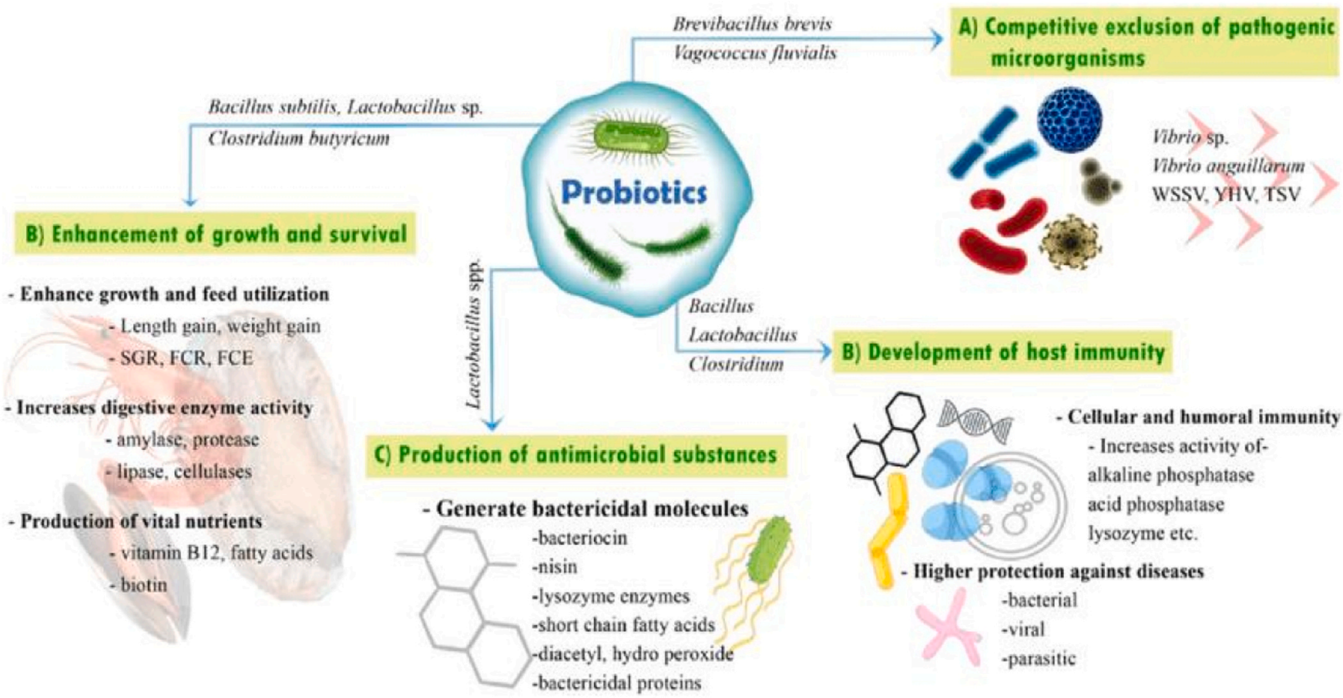

Fig.:1. Mode of action of probiotic (Sumon et al., 2022).

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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