Next-Generation Probiotics: The Future of Sustainable Aquaculture

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Abstract- Aquaculture plays a crucial role in meeting the growing global demand for seafood and contributes significantly to food security and economic development. However, the intensification of aquaculture practices has brought several challenges, including frequent disease outbreaks, environmental pollution, and the overuse of antibiotics—leading to the rise of antibiotic-resistant pathogens. These issues threaten the sustainability and long-term viability of the industry. To address these concerns, probiotics have emerged as environmentally friendly alternatives to conventional treatments. Traditional probiotics have been used to improve gut health, enhance immunity, and maintain water quality. However, their effectiveness is often limited by factors such as strain specificity and environmental conditions. Recent advances in microbiome research and biotechnology have introduced *next-generation probiotics* (NGPs), including genetically modified strains, host-specific microbes, and synbiotic formulations. These NGPs offer enhanced precision, better colonization ability, and targeted functionality, such as improved disease resistance, nutrient assimilation, and environmental resilience. This review discusses the evolution of probiotics in aquaculture, focusing on the concept, mechanisms, and applications of NGPs. It also highlights current challenges, regulatory considerations, and future directions. The integration of NGPs into aquaculture represents a promising strategy for developing more sustainable, efficient, and health-oriented production systems.

Keywords: Next-Generation Probiotics, Microbiome, Aquaculture, Sustainability

1. INTRODUCTION

Aquaculture has emerged as a critical component of global food production, playing a vital role in supplying high-quality, protein-rich seafood to meet the dietary needs of a growing population. It significantly contributes to food security, rural livelihoods, and economic growth. However, the rapid intensification and expansion of aquaculture systems have brought forth a series of challenges that threaten their sustainability. These include frequent disease outbreaks, poor water quality management, overreliance on chemical treatments, and the excessive use of antibiotics. Such practices have led to the development of antibiotic-resistant pathogens, bioaccumulation of harmful substances, and serious ecological imbalances. In addition to compromising aquatic animal health and productivity, these issues also pose substantial risks to human health and the environment [1].

In light of these challenges, the aquaculture industry has increasingly turned toward sustainable alternatives. One promising solution is the use of probiotics—live microorganisms that, when administered in adequate amounts, confer health benefits to the host. Conventional probiotics, including strains of *Lactobacillus*, *Bacillus*, and *Saccharomyces*, have shown positive effects on gut microbiota balance, immune modulation, pathogen inhibition, and water quality enhancement [2].

However, the efficacy of traditional probiotics is often inconsistent due to environmental variability and host-specific responses. Recent advancements in microbiome research, next-generation sequencing, metagenomics, and synthetic biology have enabled the development of *next-generation probiotics* (NGPs). These include genetically engineered strains, host-specific microbes, and tailored microbial consortia designed for precise functionality and improved colonization. NGPs offer greater potential in enhancing disease resistance, promoting growth, optimizing nutrient utilization, and ensuring environmental sustainability. This review explores the concept, mechanisms, applications, and future prospects of next-generation probiotics in aquaculture, highlighting their role as transformative tools for sustainable and health-focused aquatic farming [3,4].

2. CONVENTIONAL VS. NEXT-GENERATION PROBIOTICS

Probiotics have long been used in aquaculture as natural alternatives to antibiotics and chemical treatments. Conventional probiotics typically consist of naturally occurring beneficial microorganisms such as *Lactobacillus*, *Bacillus*, *Pseudomonas*, and *Saccharomyces* species. These strains help improve gut health, enhance immune responses, inhibit pathogenic microbes through competitive exclusion, and contribute to water quality maintenance. However, their performance can be inconsistent due to factors like species specificity, environmental variability, and limited colonization capacity [7].

In contrast, Next-Generation Probiotics (NGPs) represent an advanced approach driven by developments in microbiome science, metagenomics, and synthetic biology. NGPs may include genetically engineered strains, host-specific microbes, designer microbial consortia, or synbiotics (combinations of probiotics and prebiotics). Unlike conventional strains, NGPs are selected or engineered for targeted functionality, such as precise modulation of host immunity, enhanced nutrient metabolism, and efficient degradation of waste compounds. They are designed for better survivability, colonization, and specific interaction with the host microbiota[8].

While conventional probiotics offer general benefits, NGPs aim to deliver tailored, reliable, and high-performance solutions to meet the complex needs of modern aquaculture. As research progresses, NGPs are expected to play a pivotal role in developing sustainable, resilient, and health-optimized aquaculture systems.

Aspect	Conventional Probiotics	Next-Generation Probiotics
Origin	Naturally occurring beneficial microbes	Includes novel, engineered, or host-specific strains
Mechanism	Competitive exclusion, enzyme production	Tailored genetic traits, signaling modulation
Customization	Generalized for species	Precision-targeted based on host microbiome
Delivery	Feed additives or water inoculants	Encapsulation, biofilms, or genetic vectors

3. MECHANISMS OF ACTION

Next-generation probiotics (NGPs) offer advanced and targeted mechanisms to enhance the health and sustainability of aquaculture systems. Unlike conventional probiotics, which rely on general modes of action, NGPs are designed or selected for specific, high-impact biological functions.

One of the key mechanisms is gut microbiota modulation, where NGPs help establish a stable and beneficial microbial community, outcompeting harmful pathogens. They also produce antimicrobial compounds such as bacteriocins and organic acids that inhibit or kill pathogens directly. Some NGPs disrupt quorum sensing—the communication system among pathogenic bacteria—thereby preventing biofilm formation and virulence expression.

NGPs can also stimulate host immune responses, both at the mucosal and systemic levels, by enhancing phagocytosis, antibody production, and cytokine regulation. Certain engineered strains are capable of producing enzymes like proteases and cellulases, improving nutrient absorption and feed efficiency.

Another important mechanism involves bioremediation, where probiotics degrade harmful compounds like ammonia, nitrites, and hydrogen sulfide, thus improving water quality. Host-specific NGPs show improved colonization and persistence in the gastrointestinal tract, ensuring long-term benefits.

These multifaceted actions position NGPs as powerful tools to improve animal health, growth performance, and environmental resilience in modern aquaculture.

4. APPLICATIONS

Next-generation probiotics (NGPs) have emerged as promising tools to address key challenges in aquaculture, offering targeted and efficient solutions for enhancing fish and shellfish health, improving production efficiency, and promoting environmental sustainability. Their applications span multiple aspects of aquaculture management.

1. Disease Prevention and Control:
   NGPs can be designed to produce antimicrobial peptides, bacteriocins, or interfere with quorum sensing, directly inhibiting pathogenic bacteria such as *Vibrio*, *Aeromonas*, and *Pseudomonas* species. By strengthening the gut microbiota and immune responses of aquatic animals, NGPs significantly reduce the incidence of infections, thereby minimizing reliance on antibiotics[3,11].
2. Growth Promotion and Feed Efficiency:
   Certain NGPs are engineered or selected for their ability to secrete digestive enzymes (proteases, lipases, amylases), enhancing nutrient digestion and absorption. This leads to improved feed conversion ratios, faster growth rates, and lower production costs [5].
3. Immune System Modulation:
   NGPs interact with host immune cells, promoting the production of cytokines, immunoglobulins, and phagocytic activity. This strengthens the host's innate and adaptive immune defenses, particularly in stress-prone environments such as intensive farming systems [6,9].
4. Water Quality Management:
   Specific probiotic strains are capable of degrading toxic nitrogenous compounds like ammonia and nitrite, or breaking down organic waste in culture systems. Their use improves water quality and reduces the risk of disease caused by poor environmental conditions [1].
5. Larval Rearing and Broodstock Management:
   NGPs are particularly useful in hatcheries, where microbial stability is critical. They enhance larval survival, improve gut development, and support reproductive health in broodstock.
6. Biofloc and Recirculating Aquaculture Systems (RAS):
   In these intensive systems, NGPs help maintain microbial balance and reduce sludge formation, supporting system stability and reducing environmental impact.

5. RECENT ADVANCES

Recent years have witnessed significant advancements in the development and application of next-generation probiotics (NGPs) in aquaculture, driven by breakthroughs in micro biome science, genomics, and biotechnology. These advances are transforming traditional approaches to disease management, nutrition, and sustainability in aquaculture systems.

1. Microbiome and Metagenomic Profiling:

High-throughput sequencing and metagenomic analyses have enabled the precise identification of beneficial microbial communities associated with healthy fish and shrimp. This allows for the selection of host-specific probiotic strains tailored to individual species, developmental stages, or environmental conditions, enhancing efficacy and reducing variability in results.

2. Synthetic Biology and Genetic Engineering:

Synthetic biology tools, including CRISPR-Cas systems, have enabled the creation of engineered probiotic strains with enhanced functional traits. These include the ability to produce antimicrobial compounds, degrade specific toxins, or express immune-stimulating molecules. Such designer strains offer targeted solutions for disease control and nutrient optimization.

3. Synbiotic Formulations:

Recent studies have shown the synergistic benefits of combining next-generation probiotics with prebiotics (non-digestible food ingredients that promote beneficial bacteria). Synbiotics improve colonization efficiency, enhance immune function, and promote overall health in cultured species.

4. Encapsulation and Delivery Systems:

Advanced encapsulation techniques, such as microencapsulation and nano-formulations, have improved the stability and delivery of NGPs. These technologies protect probiotics from harsh environmental conditions (e.g., feed processing or acidic stomach pH) and ensure their targeted release in the gut.

5. Application in Intensive Systems:

NGPs are increasingly used in high-density systems like Biofloc technology (BFT) and recirculating aquaculture systems (RAS), where microbial management is critical. They help maintain water quality, reduce organic load, and stabilize the microbial community.

These innovations are paving the way for precision aquaculture, where NGPs play a central role in creating resilient, productive, and environmentally friendly farming systems.

6. Challenges and Limitations

Despite the promising potential of next-generation probiotics (NGPs) in improving aquaculture sustainability and productivity, several challenges and limitations hinder their widespread adoption and practical implementation.

1. Regulatory and Safety Concerns:

Many NGPs involve genetically modified organisms (GMOs), raising concerns about biosafety, environmental impact, and public acceptance. In many countries, there is a lack of clear and standardized regulatory frameworks for evaluating and approving genetically engineered microbial products for aquaculture use. This regulatory uncertainty can delay commercialization and adoption.

2. Ecological Risks:

The introduction of novel or engineered microbes into aquatic systems may disrupt native microbial communities or lead to unintended ecological consequences, such as horizontal gene transfer or the emergence of new pathogens. Long-term studies are required to evaluate the environmental safety of these interventions.

3. Host-Specificity and Variability:

NGPs often need to be tailored to specific host species, developmental stages, or rearing conditions. A probiotic effective in one fish species or environment may not work in another. This specificity increases development time, research costs, and limits cross-species applicability.

4. Production and Formulation Challenges:

Maintaining the viability and stability of NGPs during storage, feed processing, and administration can be technically difficult. Advanced encapsulation and delivery technologies are still evolving and may not yet be cost-effective for large-scale aquaculture operations.

5. High Cost and Limited Accessibility:

The development of next-generation probiotics involves sophisticated techniques such as genome editing, metagenomics, and synthetic biology, making them expensive to develop and produce. This limits their availability, particularly for small-scale or resource-limited farmers.

6. Knowledge Gaps:

Although research is growing, a comprehensive understanding of host–microbiome–environment interactions is still lacking. More in vivo studies and field trials are needed to optimize NGP performance under commercial aquaculture conditions.

Addressing these challenges is essential for realizing the full potential of NGPs in aquaculture.

7. Future Perspectives

Next-generation probiotics (NGPs) hold great promise for transforming aquaculture into a more sustainable, efficient, and health-conscious industry. As research progresses and technologies mature, the future of NGPs lies in their integration into precision aquaculture and their alignment with global sustainability goals.

1. Personalized Probiotic Approaches:

Advancements in micro biome sequencing and data analytics are paving the way for personalized probiotic formulations tailored to specific fish or shrimp species, life stages, and environmental conditions. This will enable targeted modulation of the host micro biota for optimal health and performance.

2. Microbiome Engineering:

Future developments may allow for intentional design and manipulation of microbial communities in the gut and rearing environment. By combining NGPs with microbial ecology insights and synthetic biology, it will be possible to create stable, beneficial micro biomes that resist pathogens and improve nutrient utilization[10].

3. AI and Big Data Integration:

Artificial intelligence and machine learning tools can accelerate probiotic discovery by analyzing vast microbiome datasets. Predictive models can help identify optimal probiotic strains and combinations, enhancing precision in probiotic applications.

4. Sustainable Intensification:

NGPs will play a central role in the sustainable intensification of aquaculture by reducing the dependency on antibiotics, improving feed efficiency, and mitigating environmental impacts. Their application in intensive systems such as Biofloc technology (BFT) and recirculating aquaculture systems (RAS) will further enhance system stability and productivity.

5. Regulatory Framework Development:
As the field evolves, clearer regulatory guidelines and safety assessment protocols will likely emerge, enabling smoother commercialization and global acceptance of genetically engineered or designer probiotics.

6. Holistic Health Management:
Future NGPs may be integrated with vaccines, immunostimulants, and functional feeds to provide a comprehensive health management strategy that supports both disease prevention and enhanced growth.

8. CONCLUSION

Next-generation probiotics (NGPs) mark a significant advancement in sustainable aquaculture, offering targeted solutions for disease prevention, growth promotion, and environmental management. Leveraging microbiome research, synthetic biology, and precision delivery systems, NGPs provide more effective and reliable benefits than conventional probiotics. Despite current challenges related to regulatory approval, ecological concerns, and cost, ongoing research and technological progress are expected to overcome these barriers. The integration of NGPs into aquaculture practices has the potential to enhance productivity, reduce antibiotic dependence, and promote long-term ecological balance—ultimately contributing to a more resilient and sustainable global seafood supply. Overall, NGPs offer a sustainable, multi-functional approach to modern aquaculture, aligning productivity with ecological and animal welfare considerations.

REFERENCE

[1] FAO (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/cc0461en/cc0461en.pdf

[2] Pérez-Sánchez, T., Mora-Sánchez, B., & Balcázar, J. L. (2018). Biotechnological insights into the development of next-generation probiotics for sustainable aquaculture. *Current Opinion in Biotechnology*, 61, 289–295. https://doi.org/10.1016/j.copbio.2019.01.002

[3] Hoseinifar, S. H., Sun, Y. Z., Wang, A., & Zhou, Z. (2018). Probiotics as means of diseases control in aquaculture, a review of current knowledge and future perspectives. *Frontiers in Microbiology*,9,2429.https://doi.org/10.3389/fmicb.2018.02429

[4] Wu, S., Gao, T., Zheng, Y., Wang, W., Cheng, Y., & Wang, G. (2021). Synthetic biology approaches for engineering beneficial microbial consortia for aquaculture. *Biotechnology Advances*, 53, 107842. https://doi.org/10.1016 /j.biotechadv.2021.107842

[5] Dawood, M. A. O., Koshio, S., & Esteban, M. Á. (2018). Beneficial roles of feed additives as immunostimulants in aquaculture: a review. *Reviews in Aquaculture*, 10(4),950–974.

[6] Dawood, M. A. O., Koshio, S., & Esteban, M. Á. (2018). Beneficial roles of feed additives as immunostimulants in aquaculture: a review. *Reviews in Aquaculture*, 10(4),950–974. https://doi.org/10.1111/raq.12209

[7] Hai,N.V.(2015). *The use of probiotics in aquaculture.* Journal of Applied Microbiology, 119(4), 917–935. https://doi.org/ 10.1111/ jam. 12886

[8] Wu, S., Gao, T., Zheng, Y., Wang, W., Cheng, Y., & Wang, G. (2021). Synthetic biology approaches for engineering beneficial microbial consortia for aquaculture. Biotechnology Advances, 53,107842. https://doi.org/10.1016/ j.biotechadv. 2021.107842

[9] Zepeda-Rodríguez, A., Moyano, F. J., Martínez, T. F., & Cordero, H. (2021). *Next-generation probiotics in aquaculture: the new frontier for microbiome modulation and pathogen control.* Microorganisms, 9(5), 1083. https://doi.Org /10.3390/microorganisms9051083

[10] Dahiya,T., Kaur, S., & Choudhury,T.G.(2021). Next-generation probiotics: future of sustainable aquaculture. Probiotics and Antimicrobial Proteins, 13, 1303–1317. https://doi.org/10.1007 /s12602-021-09791-5

[11] Van Doan, H., Hoseinifar, S. H., Dawood, M. A. O., Chitmanat, C., & Tayyamath,A.(2020). *Probiotic Bacillus species improved the growth performance, immunity, and disease resistance in Nile tilapia (Oreochromis niloticus).* Fish & Shellfish Immunology, 104, 36–45. https://doi.org/10.1016/j.fsi.2020.06.030