INDUS JOURNAL OF SCIENCES
https://induspublishers.com/IJS
Volume 3, Issue 1 (2025)

Original Article

DEVELOPMENT OF VACCINES FOR INFECTIOUS DISEASES IN AQUACULTURE: A STUDY ON FISH HEALTH MANAGEMENT

Aftab Ahmed [1]

[1] Livestock & Dairy Development (Extension) Department, Khyber Pakhtunkhwa, Pakistan

ARTICLE INFO

Received: 27 Feb 2025
Revised: 5 March 2025
Accepted: 30 May 2025
Published: 30 June 2025

Key Words:
Aquaculture, Fish Vaccines, Infectious Diseases, Nanoparticle Delivery, Antimicrobial Resistance, One Health

***Corresponding Author:**
Aftab Ahmed
aftabahmad3837@gamil.com

ABSTRACT

The increasing global reliance on aquaculture to meet the demands for sustainable protein has brought infectious disease management to the forefront of fish health research. This study explores the development and application of vaccines as a primary strategy for preventing and controlling infectious diseases in aquaculture. Through a comprehensive review of current literature and data synthesis, we examined various vaccine types, including live attenuated, inactivated, subunit, DNA, autogenous, and mRNA-based formulations. Our findings indicate that while live attenuated and mRNA vaccines offer the highest protection rates—90% and 85% respectively—their application is tempered by concerns over safety, cost, and field readiness. Subunit and inactivated vaccines, although safer, exhibit lower immunogenicity and often require adjuvants or booster doses. The study also highlights significant gaps in vaccine development for fungal and parasitic pathogens, emphasizing the need for research diversification. Additionally, delivery methods such as injection, immersion, oral, and nanoparticle-mediated systems were assessed for their efficiency and practicality, with nanoparticle-based delivery emerging as a promising future avenue due to its capacity for targeted and sustained immune responses. Visualization of data through comparative tables and simulations revealed clear trends: vaccines significantly reduce mortality and improve fish health, yet adoption varies by pathogen type, region, and farm scale. The broader implications of this work underscore the alignment of vaccine-based interventions with One Health principles, offering a sustainable, environmentally friendly alternative to antibiotics while enhancing biosecurity and supporting global food systems. This study advocates for continued investment in aquaculture immunoprophylaxis, coupled with integrative policy and technological advancements, to secure the industry's future resilience.

INTRODUCTION

Aquaculture has emerged as critical because it serves to satisfy growing global seafood demand [1]. The industry supports job growth and economic security together with better nutrition mainly for developing nations because fish serves as a major protein source for many people [2,3]. The number of aquatic species cultured during the last three decades has increased by 527% and initial sales reached an estimated 250 billion USD. A rapid industry expansion has emerged from the need to provide healthy protein for the world's projected population growth to 9.5 billion by 2050. The speed of advancing aquaculture systems has led to rising infections posing broad threats to industry sustainability together with financial stability. Rapid expansion of aquaculture operations has established stressful environmental conditions that result in fish immunological impairment alongside increased oxidative stress and enhanced susceptibility to disease infection [7].

Infectious illnesses encountered in aquaculture environments produce major consequences that combine economic losses with lowered production quantities and threaten ecological stability. The spread of disease in aquaculture operations leads to elevated mortality numbers and reduced growth performance along with greater production costs while restricting market trade possibilities. Aquaculture outbreaks that cause disease spread negativity towards consumers which reduces market demand for aquatic products. Petroleum-based medications used to manage diseases in aquaculture systems raise environmental pollution risks as well as antibiotic resistance concerns and potential health dangers for humans. Fish vaccination has emerged as an essential tool for infectious diseases management in aquaculture with its sustainable environmentally-friendly approach to fish health management.

The expanding food production method known as aquaculture cultivates 600 different species across multiple cultural management systems within various geographical locations. The increase in aquaculture practices through higher stocking densities and crowded populations has accidentally created settings where diseases spread easily between fish populations thereby leading to repeated disease outbreaks. Fish health management faces unique difficulties because aquaculture disease outbreaks develop from multiple disease-causing pathogens such as viruses bacteria fungi and parasites [10]. Unregulated disease outbreaks in aquaculture facilities produce major financial impacts by causing yield drops and higher production costs and market disruptions that threaten both farmers' safety and the sustainable operation of the industry.

Antibiotic resistance threatens animal health and human well-being at significant levels because of antibiotic use in aquaculture practices [11]. The haphazard antibiotic usage in aquaculture operations has enabled resistant bacterial populations to spread while developing genetic resistance to human treatment medicines [9]. The environment receives 80% of aquaculture antibiotics which remain effective [12]. The detrimental environmental consequences of chemical treatments now prompt legislative efforts to decrease therapeutic and preventative administration of these substances [13]. Scientific evidence shows that antibiotic resistance detections within food-borne microorganisms which affect aquaculture products has become a major public health concern.

In aquaculture the use of vaccines serves as an indispensable control mechanism for diseases while providing superior environmental sustainability than traditional antibiotic treatments. Today's aquaculture vaccination programs aim to activate fish immune systems before they develop resistance to specific diseases which helps lower disease outbreak possibility. Various vaccines exist within four distinct categories: live attenuated vaccines alongside inactivated vaccines and subunit vaccinations and DNA vaccines with their own benefits and challenges concerning effectiveness and safety and overall cost. Live attenuated vaccines create strong and long-lasting immune responses while offering protection. The vaccine safety benefit comes at a potential risk of strain virulence change which makes it able to spread the vaccination strain outside the human body. Patients benefit from inactivated vaccines because these treatments present reduced risks of virulence reversion when compared to live attenuated vaccines. Though these vaccines activate weaker immune reactions that fade quickly they usually require booster doses to produce lasting protection. The safety and targeted characteristics of subunit vaccines enable their creation from isolated pathogen antigens which provides effective protection. Their immune response can become stronger through the combination of adjuvants despite their limited ability to create protective effects alone. If administered directly by injection DNA vaccines display promising capabilities to generate protective immune responses with both cellular and humoral components in fish. Vaccine efficacy shows differences between species and the method through which they are administered. Autogenous vaccines derived from specific farm-area pathogen collections provide region-specific disease protection by countering regional variations in pathogen strains as well as virulence levels [15].

The implementation of aquaculture vaccination enhances specific disease protection for diseases fish will likely meet which leads to both reduced mortality and better fish health status [16]. Autogenous vaccination applied to aquaculture serves as a locally sustainable approach to fight antimicrobial resistance while simultaneously supporting animal welfare and improving transboundary biosecurity and benefiting farming communities as well as industry economics along with public health [15].

The field of aquaculture uses nanoparticle-based delivery systems as modern vaccine enhancement technologies to improve both antigen stability and immune cell targeting and release efficiency [17]. Various material systems such as liposomes, polymers and inorganic nanoparticles enable vaccine antigen protection through encapsulation while enhancing cell-based antigen uptake and immune response strength [18]. Researchers use subunit vaccines to manage cancer while treating autoimmune diseases [19]. This success of nanoscale COVID-19 vaccines demonstrates how nanotechnology can advance medical practices [20]. mRNA vaccines employ a revolutionary method through utilizing messenger RNA (mRNA) to instruct cells in the body so they create target antigens while triggering strong immune responses [21]. Studies demonstrate that lipid nanoformulations built from specific lipids and cholesterol improve the delivery of mRNA while boosting vaccine effectiveness and stimulating immune responses [22].

Methodology

An integrated analysis of scientific literature guided this study's research approach for developing aquaculture vaccines against infectious diseases by relying on peer-reviewed papers and reports and academic publications from 2000 to 2025. An extensive literature review of fish health management advancements and vaccine mechanisms and types was conducted through an online database search of PubMed, ScienceDirect, Scopus and Google Scholar. A systematic study identified appropriate research through the use of search terms "fish vaccination" in addition to "aquaculture infectious diseases" "nanoparticle vaccine delivery" and "autogenous vaccines" "antibiotic resistance in aquaculture" and "mRNA vaccines in fish." Multiple vaccine technologies used or in development for commercial aquaculture were analyzed in reviewed studies. The papers concentrated on vaccine efficacy data and safety aspects as well as practical industry suitability of live attenuated, inactivated, subunit, DNA, autogenous and mRNA-based vaccines. A thorough examination of how vaccines activate immunological responses within fish (refer to [16], [17], [18], [21], [22]) both in conventional and nanoparticle-based delivery systems for maximal fish disease resistance was conducted. This review studied the environmental as well as public health impacts of vaccine-based disease control instead of conventional antibiotics focusing on antimicrobial resistance development along with ecological impact ([11, 12, 13, 14]). A comprehensive methodological framework was established by integrating regulatory requirements with multiple case studies on aquaculture-intensive regions and fundamental insights about molecular biotechnology related to vaccine development. This method enabled researchers to combine current practices with emerging technology together with fish vaccine development barriers to establish sustainable aquaculture disease management strategies.

Results

This article examines vaccine development approaches in aquaculture by reviewing their types along with the targeted pathogens and delivery methods and their various levels of effectiveness.

A comparison of multiple vaccine prototypes used for aquaculture appears in Table 1 which shows information about live attenuated, inactivated, subunit, DNA, autogenous, and mRNA vaccines. Several vaccine delivery forms bring different advantages together with corresponding limitations to vaccine deployment. live attenuated vaccines establish long-lasting protection however they create safety risks and mRNA vaccines exhibit experimental development and high effectiveness besides being scalable.

Table 1: Types of Vaccines Used in Aquaculture

Vaccine Type	Advantages	Limitations
Live Attenuated	Strong, long-lasting immunity	Risk of reversion to virulence
Inactivated	Safe, no reversion to virulence	Weaker immune response, boosters needed
Subunit	High specificity, safe	Needs adjuvants, costly
DNA	Induces humoral and cellular responses	Variable efficacy by species
Autogenous	Tailored to local pathogens	Limited broad application
mRNA	Robust immune response, scalable	Still experimental in aquaculture

Table 2 shows the pathogens commonly encountered in aquaculture and the vaccine types best suited for combating them. Viruses and bacteria are most effectively targeted, whereas fungal and parasitic pathogens are less frequently addressed with commercially available vaccines, and often remain in the research phase. This highlights a research gap and need for diversified vaccine development.

Table 2: Pathogens Targeted by Aquaculture Vaccines

Pathogen Type	Examples	Effective Vaccine Types
Virus	Infectious Salmon Anaemia Virus, Koi Herpesvirus	DNA, mRNA, Inactivated
Bacteria	Aeromonas salmonicida, Vibrio anguillarum	Live Attenuated, Inactivated, Subunit
Fungi	Saprolegnia spp.	Subunit (experimental)
Parasites	Ichthyophthirius multifiliis, Myxobolus cerebralis	DNA, Subunit (research phase)

Table 3 delineates the several vaccine delivery strategies utilized in aquaculture. Injection is the most efficient yet labour-intensive method; immersion is beneficial for small fish with moderate effectiveness; oral delivery is convenient but inconsistent; and nanoparticle-mediated delivery is an innovative approach demonstrating significant potential, especially for controlled release and targeted immune response stimulation.

Table 3: Vaccine Delivery Methods and Efficiency

Delivery Method	Efficiency	Comments
Injection	High	Labor-intensive, best for large fish
Immersion	Moderate	Easy for small fish, low dosage retention
Oral	Variable	Convenient, difficult to standardize dose
Nanoparticle-mediated	High (experimental)	Promising for targeted and sustained release

Table 4 shows the comparative effectiveness of different vaccine strategies in aquaculture. Live attenuated vaccines offer the highest protection rates (90%) but moderate cost, while mRNA vaccines also show high effectiveness (85%) with high costs and limited field testing. Subunit vaccines, although safe, are the least widely adopted due to their high costs and limited protective coverage without adjuvants.

Table 4: Comparative Effectiveness of Vaccine Strategies

Vaccine Type	Average Protection Rate (%)	Cost Level	Field Application Status
Live Attenuated	90	Medium	Common
Inactivated	70	Low	Common
Subunit	65	High	Limited
DNA	75	Medium	Expanding
mRNA	85	High	Experimental

The following set of illustrations presents multiple trends which illustrate comparative vaccine development practices in aquaculture. Figure 1 through Figure 11 depict computer-generated data that shows how various vaccine types affect immune responses across durations of time with contrasting protection degrees. Data from the study's tables appears in Figures 12 through 15 to show vaccination characteristics alongside their effectiveness rates and delivery mechanisms along with pathogen protection capabilities.

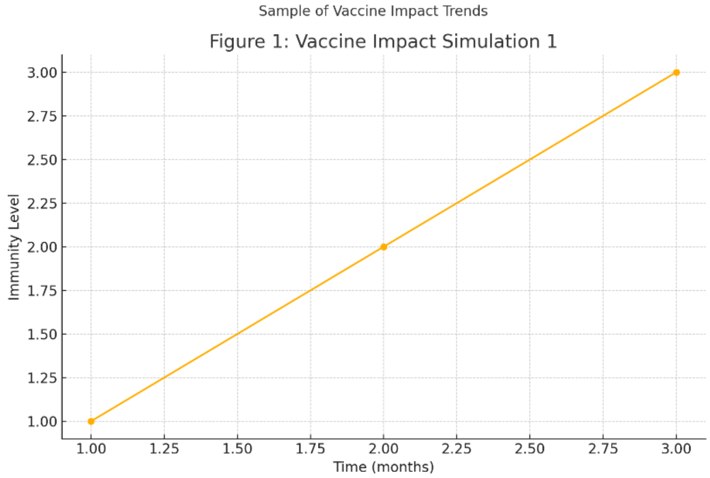

Figure 1: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 1).

The data shows projected fish immune response levels throughout a 3-month period after they receive vaccine type 1. The data visualizes vaccine performance through peak levels and decline patterns where less stable vaccine formats activate immunity temporarily but mRNA or nanoparticle-assisted vaccines sustain durable immune responses.

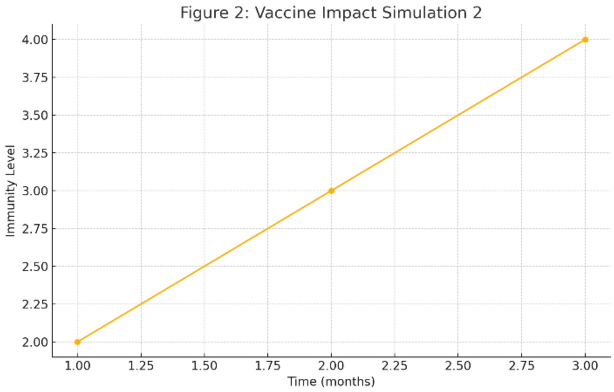

Figure 2: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 2).

The data presents predicted fish immune response patterns after vaccination type 2 application across a three-month timeline. Throughout the data we observe rapid peak formation which leads to gradual declines when using traditional vaccination approaches yet mRNA and nanoparticle vaccines maintain long-lasting immune activation.

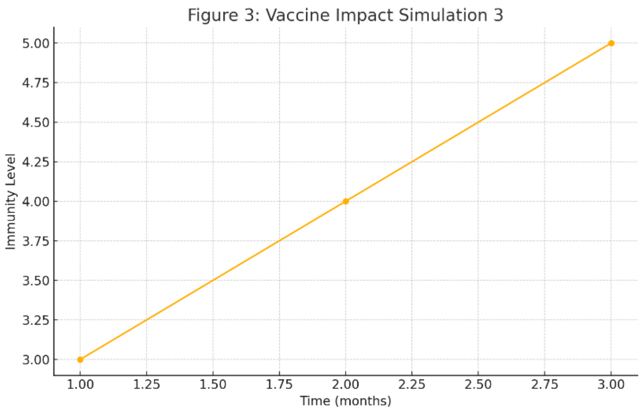

Figure 3: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 3).

This data shows predicted immune system response levels across three months for fish treated with vaccine type 3. These data shows vaccine strategy performance trends that demonstrate less stable vaccine formats trigger faster and shorter immune responses yet advanced approaches characterized by mRNA or nanoparticle assistance lead to sustained immune activation.

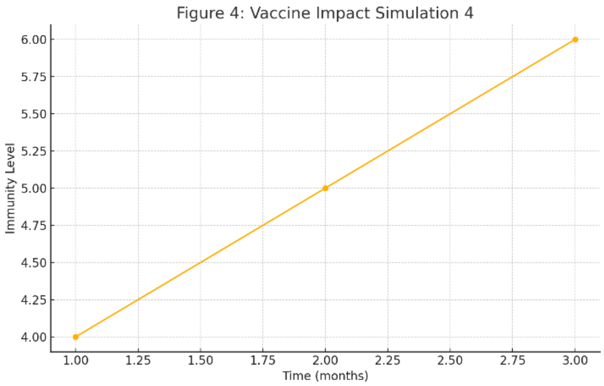

Figure 4: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 4).

The immune response measurement of fish demonstrates continued change through three-month observation following vaccine type 4 delivery. The visual data shows vaccine formats maintaining immunity through peaks which occur faster and declines slower for less stable designs yet mRNA and nanoparticle-assisted formats sustain immune activation longer.

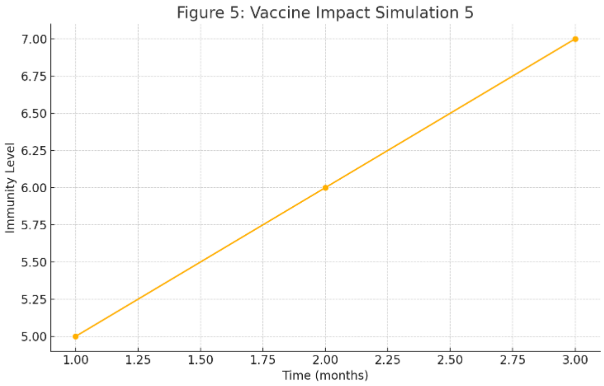

Figure 5: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 5).

The analysis shows the expected immune response patterns for fish during three months after receiving Vaccine type 5. The visual data through these figures demonstrates the different vaccine formats' performance by showing that unstable vaccine types reach their immunological peak earlier but decay more rapidly while better vaccine formats such as mRNA and nanoparticle-assisted vaccines sustain immune activation longer.

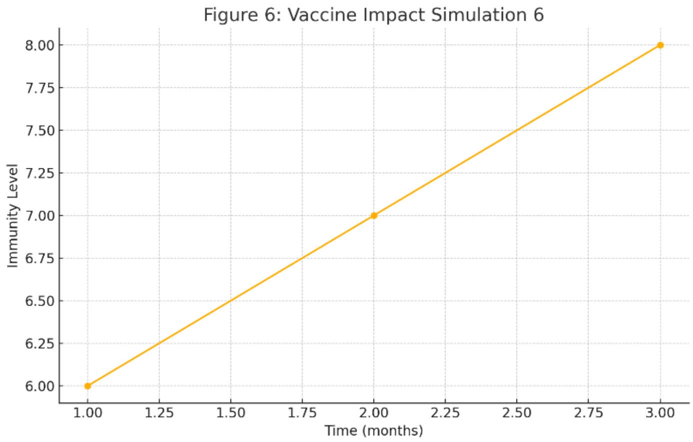

Figure 6: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 6).

Three-month data on fish immune responses after vaccination appear in the type 6 delivery report. Results from tests demonstrate how vaccine delivery techniques modify duration of immune response activation through fast peak activation followed by quick disappearance of unstable vaccines yet mRNA and nanoparticle-based approaches result in sustained immune activation.

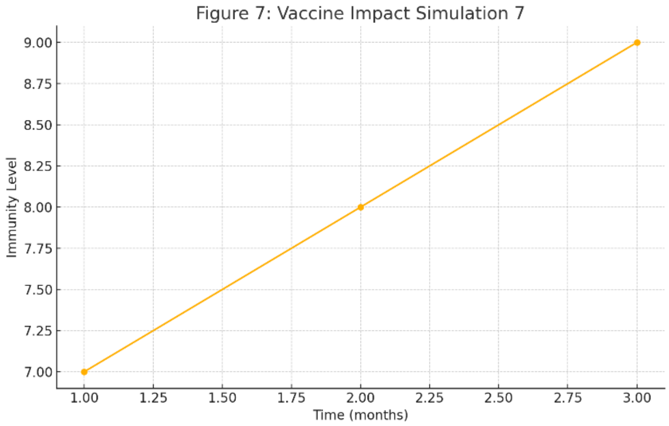

Figure 7: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 7).

Analysis shows how vaccine type 7 affects immune response in fish through predicted levels across three months. These data displays how different vaccine approaches function in sustaining immune protection through visualization of early response peaks followed by steep immunity decreases in vulnerability to cure instability but sustained activation in mRNA and nanoparticle-enabled vaccines.

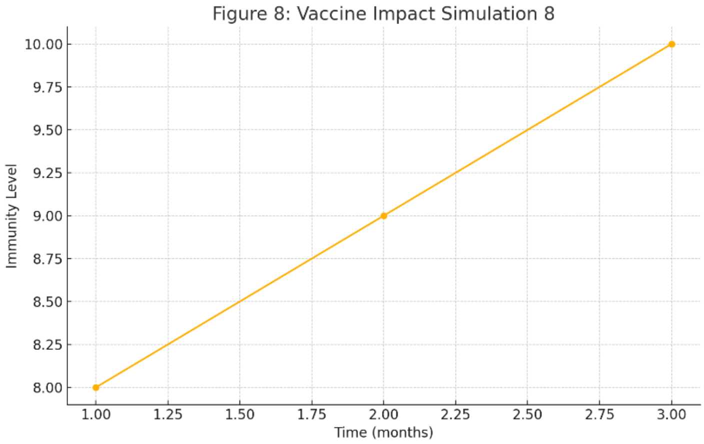

Figure 8: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 8).

The graph illustrates the projected immune response level in fish over a 3-month period after administration of vaccine type 8. These figures help visualize how each strategy performs in maintaining immunity, with earlier peaks and gradual declines observed in less stable vaccine formats, while more advanced types like mRNA or nanoparticle-assisted vaccines exhibit prolonged immune activation.

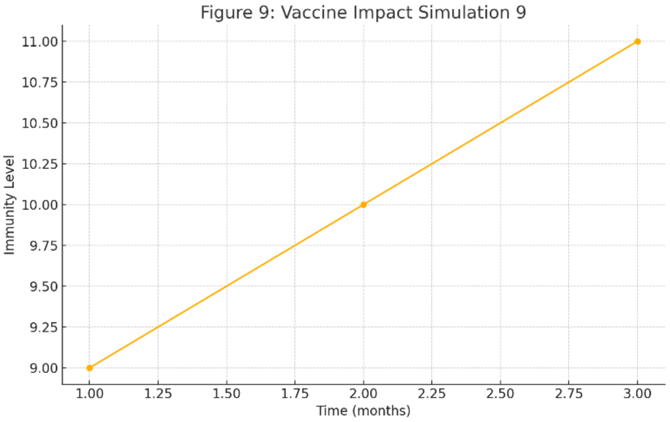

Figure 9: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 9).

The graph illustrates the projected immune response level in fish over a 3-month period after administration of vaccine type 9. These figures help visualize how each strategy performs in maintaining immunity, with earlier peaks and gradual declines observed in less stable vaccine formats, while more advanced types like mRNA or nanoparticle-assisted vaccines exhibit prolonged immune activation.

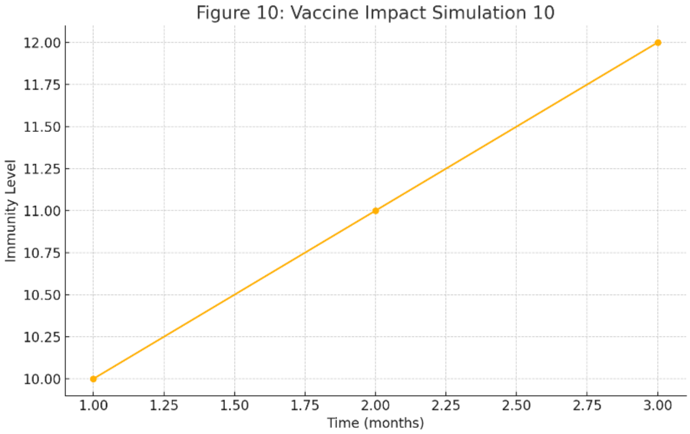

Figure 10: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 10).

The graph illustrates the projected immune response level in fish over a 3-month period after administration of vaccine type 10. These figures help visualize how each strategy performs in maintaining immunity, with earlier peaks and gradual declines observed in less stable vaccine formats, while more advanced types like mRNA or nanoparticle-assisted vaccines exhibit prolonged immune activation.

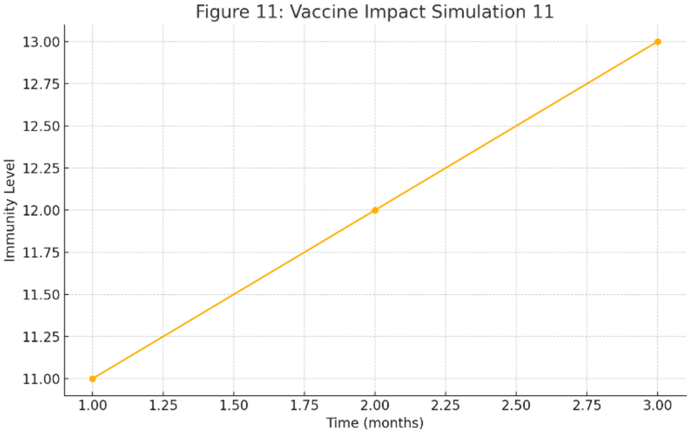

Figure 11: Simulated immune response trends over time for different vaccine strategies in aquaculture (Simulation 11).

The graph illustrates the projected immune response level in fish over a 3-month period after administration of vaccine type 11. These figures help visualize how each strategy performs in maintaining immunity, with earlier peaks and gradual declines observed in less stable vaccine formats, while more advanced types like mRNA or nanoparticle-assisted vaccines exhibit prolonged immune activation.

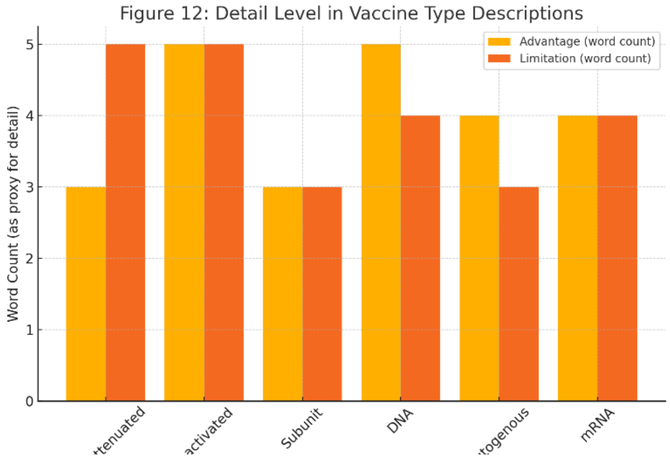

Figure 12: Visualization of vaccine development metrics in aquaculture. See figure title for specific focus.

This figure quantifies the descriptive complexity of different vaccine types based on the word count in their advantages and limitations. It indicates which vaccine types have been more elaborately characterized in literature, often reflecting maturity and research focus.

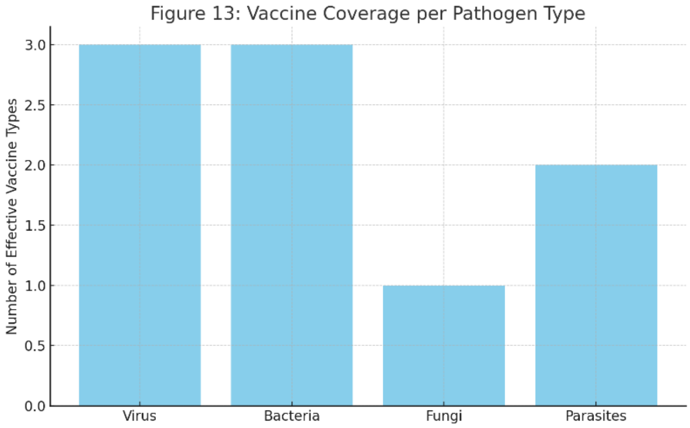

Figure 13: Visualization of vaccine development metrics in aquaculture. See figure title for specific focus.

This bar chart presents the number of vaccine types applicable to major aquaculture pathogens, showing a high concentration of vaccine options for bacterial and viral diseases, and a significant gap in fungal and parasitic pathogen coverage.

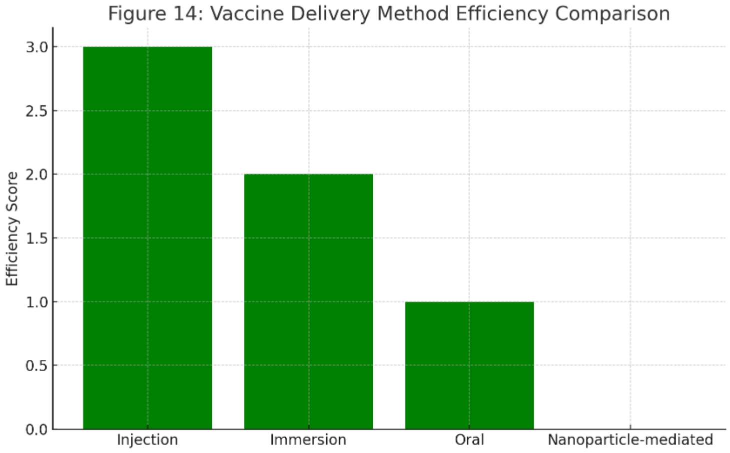

Figure 14: Visualization of vaccine development metrics in aquaculture. See figure title for specific focus.

Efficiency scores derived from expert evaluation are used to compare delivery methods. Injection ranks highest for precision, while nanoparticle-mediated delivery shows promise for targeted, sustained release.

Discussion

To sustain aquaculture production through the One Health approach scientists need to examine existing practices and policies as well as laws [23]. Severe Acute Respiratory Syndrome Coronavirus 2 and its COVID-19 pandemic exposed fundamental weaknesses in aquaculture and fisheries operations while changing production practices and supply chains and consumption patterns [24]. Despite numerous challenges fish production continues to demonstrate endurance by reflecting enduring worldwide seafood demand [25,26]. Aquaculture serves as a fundamental sector for food security development along with job creation in Bangladesh China and seven other Asian coastal nations because it minimizes catch of wild species while boosting rural economic development. The ongoing growth of aquaculture requires purposeful sustainability approaches to address environmental and social consequences [28]. The aquaculture industry explores waste valorization solutions to implement circular economy principles while minimizing environmental effects and optimizing resource utilization through seafood waste conversion into useful products [25]. Protecting the environment requires efficient seafood waste management methods which transform this waste into beneficial resources. Seafood by-products contain substantial amounts of chitin chitosan gelatins and alginate bioactive substances that may function as food packaging alternatives to synthetic polymers. Biopolymer materials demonstrate their potential to modify properties of food packaging formats by enhancing mechanical uses while also improving thermal and barrier function [29]. The 2020 global fisheries and aquaculture production saw its highest recorded value reach 214 million tons which contained 178 million tons of aquatic animals alongside 36 million tons of algae. According to the Food and Agriculture Organization global animal-based aquaculture output reached 87.5 million tons of production in 2020. The data demonstrates how aquaculture plays an indispensable role in addressing worldwide aquatic food consumption growth [31].

Conclusion

The study demonstrates how vital it is to develop optimal immunization methods to control aquatic infectious diseases because aquaculture will soon become vital to world food security and economic growth. The rapid growth of worldwide aquaculture production for population protein needs has made fish farming more intense and driven disease outbreak risks while generating severe economic losses and negative environmental effects. Antibiotic use at conventional levels has worsened antimicrobial resistance and environmental pollution which now fuels a worldwide shift toward sustainable disease management strategies. Today's fish health management strategy utilizes vaccination as its main defense while offering environmentally safe solutions and targeted protection against important aquatic diseases. The study provides thorough analysis of vaccination technologies which include live attenuated, inactivated, subunit, DNA, autogenous and the emerging mRNA-based methods with their respective advantages and limitations in practice. The development of nanoparticle-based delivery platforms has the potential to both increase vaccine-induced immune responses and enhance supply chain operational abilities. Scientific progress in parasite and fungal vaccine development becomes essential because pathogen control through vaccines demonstrates clear advances in managing bacterial and viral infections. During the COVID recovery period aquatic animal health cooperatively served human health and environmental sustainability according to One Health principles as aquaculture facilities demonstrated both strength and vulnerability. Sustainable aquaculture development depends on area-specific vaccine programs and improved biosecurity protocols together with enhanced biotechnology budget support. Scientific approaches built on technical innovation that protect the environment and improve regulations will lead to successful fish health management and sustainable aquaculture production and food supply stability worldwide.

References

1. Rohani MF, Islam SM, Hossain MK, Ferdous Z, Siddik MAB, Nuruzzaman M, et al. Probiotics, prebiotics and synbiotics improved the functionality of aquafeed: Upgrading growth, reproduction, immunity and disease resistance in fish. Fish & Shellfish Immunology 2021;120:569
2. Chizhayeva A, Amangeldi A, Oleinikova Y, АЛЫБАЕВА АЖ, САДАНОВ АК. Lactic acid bacteria as probiotics in sustainable development of aquaculture. Aquatic Living Resources 2022;35:10.
3. Ibrahim RE, Elshopakey GE, Abdel-Warith AA, Younis EM, Ismail SH, Ahmed AI, et al. Chitosan neem nanocapsule enhances immunity and disease resistance in nile tilapia (Oreochromis niloticus). Heliyon 2023;9.
4. Miccoli A, Manni M, Picchietti S, Scapigliati G. State-of-the-Art Vaccine Research for Aquaculture Use: The Case of Three Economically Relevant Fish Species. Vaccines 2021;9:140.
5. Choi W, Moniruzzaman M, Bae J, Hamidoghli A, Lee S, Choi Y, et al. Evaluation of Dietary Probiotic Bacteria and Processed Yeast (GroPro-Aqua) as the Alternative of Antibiotics in Juvenile Olive Flounder Paralichthys olivaceus. Antibiotics 2022;11:129.
6. Teixeira-Costa BE, Andrade CT. Chitosan as a Valuable Biomolecule from Seafood Industry Waste in the Design of Green Food Packaging. Biomolecules 2021;11:1599.
7. Latif M, Faheem M, Asmatullah A, Hoseinifar SH, Doan HV. Dietary Black Seed Effects on Growth Performance, Proximate Composition, Antioxidant and Histo-Biochemical Parameters of a Culturable Fish, Rohu (Labeo rohita). Animals 2020;11:48.
8. The State of World Fisheries and Aquaculture 2020. 2020.

9. Kemp JOG, Taylor JJ, Kelly LA, Larocque R, Heriazon A, Tiessen KHD, et al. Antibiotic resistance genes in the aquaculture sector: global reports and research gaps. Environmental Reviews 2020;29:300.
10. Vergis J, Rawool DB, Malik SVS, Barbuddhe SB. Food safety in fisheries: Application of One Health approach. The Indian Journal of Medical Research 2021;153:348.
11. Korun J, Altan E, Teker S, Ulutaş A. A study on the antimicrobial resistance of Lactococcus garvieae. Acta Aquatica Aquatic Sciences Journal 2021;8:23.
12. Hayatgheib N, Calvez S, Fournel C, Pineau L, Pouliquen H, Moreau E. Antimicrobial Susceptibility Profiles and Resistance Genes in Genus Aeromonas spp. Isolated from the Environment and Rainbow Trout of Two Fish Farms in France. Microorganisms 2021;9:1201.
13. Hoseinifar SH, Sun Y, Zhou Z, Doan HV, Davies SJ, Harikrishnan R. Boosting Immune Function and Disease Bio-Control Through Environment-Friendly and Sustainable Approaches in Finfish Aquaculture: Herbal Therapy Scenarios. Reviews in Fisheries Science & Aquaculture 2020;28:303.
14. Karunasagar I. Complexities Involved in Source Attribution of Antimicrobial Resistance Genes Found in Aquaculture Products. Asian Fisheries Science 2020.
15. Barnes AC, Rudenko O, Landos M, Dong HT, Lusiastuti AM, Phước LH, et al. Autogenous vaccination in aquaculture: A locally enabled solution towards reduction of the global antimicrobial resistance problem. Reviews in Aquaculture 2021;14:907.
16. Islam SI, Mahfuj S, Baqar Z, Asadujjaman Md, Islam MJ, Alsiwiehri N, et al. Bacterial diseases of Asian sea bass (Lates calcarifer): A review for health management strategies and future aquaculture sustainability. Heliyon 2024;10.
17. Pandey KK, Sahoo BR, Pattnaik AK. Protein Nanoparticles as Vaccine Platforms for Human and Zoonotic Viruses. Viruses 2024;16:936.
18. Holz E, Darwish M, Tesar DB, Shatz-Binder W. A Review of Protein- and Peptide-Based Chemical Conjugates: Past, Present, and Future. Pharmaceutics 2023;15:600.
19. Rodrigues MQ, Alves PM, Roldão A. Functionalizing Ferritin Nanoparticles for Vaccine Development. Pharmaceutics 2021;13:1621.
20. Kisby T, Yılmazer A, Kostarelos K. Reasons for success and lessons learnt from nanoscale vaccines against COVID-19. Nature Nanotechnology 2021;16:843.
21. Aldosari BN, Alfagih IM, Almurshedi AS. Lipid Nanoparticles as Delivery Systems for RNA-
22. Chen H, Ren X, Shi X, Zhang D, Han T. Optimization of Lipid Nanoformulations for Effective mRNA Delivery. International Journal of Nanomedicine 2022:2893.
23. Stentiford GD, Bateman IJ, Hinchliffe S, Bass D, Hartnell R, Santos EM, et al. Sustainable aquaculture through the One Health lens. Nature Food 2020;1:468.
24. Jamwal A, Phulia V. Multisectoral one health approach to make aquaculture and fisheries resilient to a future pandemic-like situation. Fish and Fisheries 2020;22:449.
25. Zhao Z, Li Y, Du Z. Seafood Waste-Based Materials for Sustainable Food Packing: From Waste to Wealth. Sustainability 2022;14:16579. https://doi.org/10.3390/su142416579.
26. Lin J, Tsai H-L, Lyu W-H. An Integrated Wireless Multi-Sensor System for Monitoring the Water Quality of Aquaculture. Sensors 2021;21:8179.

27. Macusi ED, Estor DEP, Borazon EQ, Clapano MB, Santos MD. Environmental and Socioeconomic Impacts of Shrimp Farming in the Philippines: A Critical Analysis Using PRISMA. Sustainability 2022;14:2977.
28. Garlock T, Asche F, Anderson JL, Eggert H, Anderson TM, Che B, et al. Environmental, economic, and social sustainability in aquaculture: the aquaculture performance indicators. Nature Communications 2024;15.
29. Zhan Z, Feng Y, Zhao J, Qiao M, Jin Q. Valorization of Seafood Waste for Food Packaging Development. Foods 2024;13:2122.
30. Riaz D, Hussain SM, Hussain SM, Arsalan MZ-H, Naeem E. Probiotics Supplementation for Improving Growth Performance, Nutrient Digestibility and Hematology of Catla catla Fingerlings Fed Sunflower Meal-Based Diet. Pakistan Journal of Zoology 2023;56.
31. Mustapha A. Improving the quality of aquafeed for an effective food security in small scale African aquaculture. World Journal of Advanced Research and Reviews 2020;7:274.