**Review Article**

**Immune Systems and Vaccination Strategies in Fish: A Comprehensive Overview**

**Abstract**

Fish possess a unique immune system that, while somewhat similar to mammals, exhibits distinct characteristics. This review paper explains the complexities of fish immunity, highlighting the innate and adaptive immune responses that protect against a variety of pathogens, including bacteria, viruses, fungi, and parasites. Host-pathogen interactions are dynamic and critical for understanding the immune evasion strategies employed by pathogens, such as antigenic variation, molecular mimicry, and biofilm formation. Vaccination plays a crucial role in aquaculture, enhancing fish immunity against diseases through various types of vaccines, including inactivated, live, subunit, and nucleic acid vaccines. To maximize immunogenic responses, various delivery methods are employed, such as injection, immersion, and oral administration. Additionally, advancements in science and technology have led to innovative techniques aimed at increasing vaccine efficacy, including nanoparticle delivery and microencapsulation. Successful vaccination strategies have been adapted to combat significant fish pathogens, demonstrating the potential for enhancing disease resistance in aquaculture. This comprehensive overview underscores the importance of understanding fish immune systems and developing effective vaccination strategies to ensure fish health and sustainability in aquaculture practices.

**Keywords:** Immune System, Vaccination, Disease, Pathogen, Aquaculture.

**Introduction:**

Fish are cold-blooded animals that appeared during the Devonian period. They are the most diverse group of vertebrates and have organs for immunity similar to those in the mammalian immune system. The immune system is a network within an organism that detects a broad range of agents, from viruses to parasitic worms, protects against diseases, and differentiates between harmful and non-harmful agents. The study of immunology in aquatic organisms began with Metchnikoff, who observed the wounded larvae of starfish and later explored the cellular basis of the interaction between host and pathogen. Organisms have outer and inner epithelial surfaces that help defend against microorganisms and contain lectins, complement proteins, lysozyme, and antimicrobial peptides. Fish immune systems represent important comparative outgroups for understanding the evolution of the immune system (Lieschke and Trede, 2009). Most secondary lymphoid organs in fish are similar to those in mammals; however, differences in lymphatic nodules and bone marrow organs contribute to a less robust adaptive immune response in fish (Mokhtar et al., 2023). The immune system of fish contains both innate and adaptive immunity. Innate immunity acts as the primary defense line against pathogens and is non-specific in nature, whereas adaptive immunity is specific and targets particular pathogens. Physical parameters, humoral parameters, and cellular factors are the three components of the innate immune system. The fish kidney contains two parts: the anterior kidney, also called the head kidney, which is aglomerular and contains B lymphoid cells, and the posterior kidney. Antigen-presenting cells (APCs), such as macrophages or monocytes, are crucial for distinguishing between self and nonself-cells and for inhibiting foreign agents accordingly (Rauta et al., 2012).

Physical parameters

Humoral parameters

Cellular parameters

Innate immunity

Fig.1. Components of Innate immune system in fish

There are various types of pathogens that affect the health and growth of fish. These pathogens include bacteria (Aeromonas spp., Vibrio spp., Flavobacterium spp., Yersinia ruckeri), viruses (*Infectious Pancreatic Necrosis Virus* [IPNV], *Spring Viremia* of Carp Virus [SVCV], *Koi Herpesvirus* [KHV], Channel Catfish Virus [CCV]), fungi (Branchiomyces spp., Saprolegnia spp.), and parasites (*Ichthyophthirius multifiliis*, Dactylogyrus spp., Gyrodactylus spp., Trichodina spp.) (Mondal et al., 2022). Bacterial pathogens have developed various mechanisms to evade or neutralize host defences, thereby ensuring their survival within a host (Celli and Finlay 2002). These strategies include biofilm formation, surface modulation, cytokine inhibition, blockade of acquired immunity, and the utilization of specific virulence factors such as type III secretion systems and pore-forming toxins. Biofilm formation enables bacteria to create a protective matrix that shields them from immune cells and antibiotics, enhancing their resistance (Finlay and McFadden 2006).

There is a dynamic interaction between the host immune system and pathogens, making it essential to understand the relationship between host and pathogen in order to study the effects of pathogens on the host. Host-parasite interactions are intricate and influenced by various factors that can alter the dynamics in either direction. The age, behaviour, immunological condition, and environmental changes affecting the host can impact the relationship in a way that may benefit the host. Conversely, when a parasite successfully evades the host's immune response, it gains an advantage. Pathogens can enter into the fish through various routes, such as the skin, gills, and alimentary canal, and can invade the immune system. Fish immune systems recognize pathogens using pattern recognition receptors (PRRs) like Toll-like receptors (TLRs) and nucleotide-binding oligomerization domain-like receptors (NLRs). This recognition triggers an innate immune response that involves physical barriers (skin, mucous membranes) and antimicrobial substances (peptides, lysozymes, complement proteins). Immune cells then engulf foreign agents. However, pathogens have adopted various strategies to evade the immune response, such as biofilm formation and manipulation of host cells (Khan 2012).

**Immune Evasion Mechanisms of Bacteria**

1) **Antigenic Variation in Bacteria:** Antigenic variation is a common strategy employed by bacterial pathogens to evade immune responses. By changing the antigens on their surface, bacteria can avoid recognition by the immune system and establish chronic infections (Palmer et al., 2016). This can be achieved through various mechanisms, such as having multiple copies of a molecule with independent on/off switches, expressing different genes from a pool of silent copies, or constantly changing a highly variable region in a molecule.

2) **Molecular Mimicry:** Bacteria can hide themselves by expressing host-like molecules on their surface, leading to reduced recognition by the immune system. By molecular mimicry, bacteria can prevent detection by antibodies and other molecules of the innate and adaptive immune systems that have evolved to recognize foreign invaders. In some cases, it may trigger autoimmune or inflammatory responses by cross-reacting with self-antigens over time. Bacteria that employ molecular mimicry include Streptococcus pyogenes, Salmonella, Helicobacter pylori and Mycobacterium tuberculosis etc (Moran et al., 2016).

3) **Biofilm formation:** Biofilms are complex communities of bacteria encased in a slimy extracellular matrix, providing protection against the host immune system Within biofilms, bacteria exhibit increased resistance to antibiotics and immune cells. Mature biofilms are highly resistant to phagocytosis. Detached biofilm fragments can spread infection by evading immune clearance (Johnson 2008).

4) **Bacterial surface modulators:** Pathogens can alter their surface structures, such as expressing a carbohydrate capsule or modifying lipid A, to hide from immune surveillance systems and avoid recognition by Toll-Like Receptors (TLRs). This allows them to evade immune recognition and phagocytic killing. Examples of bacterial surface modulators that play a role in immune evasion are Capsular polysaccharides, LPS, Protein A, Pili/fimbriae, O-antigen capsule, Teichoic acid etc. (Kaparakis. and Ferrero 2015).

5) **Inhibition of Phagocytosis:** Phagocytosis is a crucial immune mechanism where specialized cells engulf and digest bacteria. Some bacteria have developed mechanisms to evade phagocytosis. For instance, Staphylococcus aureus produces proteins that interfere with the opsonization process, where antibodies or complement proteins coat bacteria to enhance their recognition by phagocytes. By inhibiting opsonization, S. aureus can avoid detection and destruction by immune cells.

6) **Manipulation of Host Signalling Pathways:** Bacteria can interfere with host signalling pathways to subvert the immune response. Some bacteria produce effector proteins that manipulate host cell signalling, inhibiting the production of antimicrobial peptides and interfering with cytokine signalling (Bhavsar et al., 2007). By disrupting these essential communication pathways, bacteria can create a favourable environment for their survival and replication.

7) **Inhibition of Complement System:** The complement system is a part of the innate immune response that helps clear pathogens. Bacteria like Streptococcus pneumoniae produce proteins that interfere with complement activation, preventing opsonization and subsequent phagocytosis (Blom et al., 2009).

8) **Intracellular Survival:** Many bacteria, such as Mycobacterium tuberculosis, have evolved to survive and replicate within host cells, particularly macrophages, shielding them from extracellular immune attacks like antibodies and complement proteins.

9) **Modulation of Host Cell Death:** Bacteria can induce or inhibit apoptosis in host cells to their advantage. Inducing apoptosis in immune cells can eliminate key effector cells, while inhibiting apoptosis in infected cells can prolong the survival of a niche for bacterial replication (Gao and Kwaik 2000)

10) **Secretion Systems:** Bacterial secretion systems, such as the Type III secretion system (T3SS), directly inject effector proteins into host cells. These proteins can manipulate host cell functions, helping bacteria evade detection and destruction.

11) **Blockade of acquired immunity:** Bacterial pathogens can interfere with the activation and function of B and T cells, which are key players in adaptive immunity. This can be achieved through various mechanisms, such as disrupting antigen presentation or inhibiting the activation of immune cells (Zhou et al., 2021).

12) **Resistance to Antimicrobial Peptides:** Bacteria have developed resistance mechanisms to antimicrobial peptides, an important part of the innate immune defence. Alterations in membrane composition or secretion of proteases that degrade these peptides help bacteria resist this line of defence (Joo et al., 2016).

**Vaccination in aquaculture**

A vaccine is a biologically derived preparation designed to enhance immunity against a specific disease or a group of diseases. Vaccines work as biological agents to activate the body's defenses against a particular antigen that is obtained from disease-causing infectious organisms (Czochor and Turchick, 2014). A common fish vaccination either produces or contains an antigen-binding material. The fish's innate and/or adaptive immune response against a particular disease is then triggered by this component (Ma *et al*., 2019).

**Types of vaccines**

**Inactivated or killed vaccines**

Vaccines that are inactivated or destroyed are typically created from major disease-causing microbes that are physically, chemically, or radiation-treated to make them non-infectious and incapable of replicating within or outside a host. These alterations are made without affecting the microbial agent's antigenic qualities (Tlaxca *et al.,* 2015).

**Live or attenuated vaccines**

Live vaccinations are produced using one or more bacteria or viruses that inherently possess low virulence or are attenuated to be less harmful to the desired species of fish. Disease-causing agents can be altered or made less potent by employing chemical or physical interventions, repetitive passage in cell cultures, typical conditions during culture, or the use of genetic engineering (Desmettre *et al*., 1997). Live vaccines generally exhibit higher immunogenicity than inactivated preparations, as they can replicate or enter the host, leading to more robust cellular responses associated with innate and adaptive immunity (Levine *et al*.,2004). Strong antibody responses are produced by these cell-mediated immune responses, which closely resemble a pathogen's natural infection (Collins.,1974). This provides a significant advantage for species in agriculture and aquaculture (Shoemaker *et al*., 2009).

**Subunit vaccine**

Subunit vaccines use purified fragments from microorganisms that are inherently immunogenic, enabling them to elicit immune responses in hosts when administered (Ma *et al*., 2019). As subunit vaccines cannot multiply within the host, there is no chance of infection to either the host or non-target species. Instead, they are made completely of antigenic compounds (Dungu.,2011). These vaccines can be produced under strictly regulated circumstances and freeze-dried for convenient handling, storage, and transportation without the need for refrigeration. In addition, they effectively target immune reactions on specific microbiological factors (Hansson *et al*., 2000).

**Nucleic acid vaccines**

DNA or RNA encoding the target antigen(s) makes up nucleic acid vaccinations. Since they are unable to convert to a pathogenic state, they are thought to be quite easy to manufacture and safe to be employed (Ulmer *et al.,* 2012). DNA vaccines involve the direct insertion of genetic material into the host that encodes certain pathogen antigens. This genetic material can induce protection by establishing an effective immune response in the host's cells and promoting the generation of the appropriate targeted antigens. DNA-based vaccines are made up of an expression plasmid that has a particular genome that codes for a particular antigen protein. A strong immunological response is anticipated when this protein is expressed in the host. Plasmid production is enhanced in bacterial cells, where the target gene is surrounded by components that facilitate and control its expression in eukaryotic cells (Kurath *et al*., 2008). DNA vaccines can effectively stimulate both humoral and cellular immunity. DNA vaccines can be developed more quickly and easily once a protective antigen has been found because they use molecular mechanisms that are similar to those employed by viruses to penetrate host cells(Sandoval *et al*.,2001). These vaccinations have shown to be especially efficient against fish rhabdoviruses and are often more successful in avoiding viral infections (Holvold *et al*., 2014).

The RNA vaccine has all of the necessary molecular building blocks for a messenger RNA molecule, allowing for translational expression in the cell's ribosome. These elements consist of the targeted antigen's open reading frame (ORF), which is surrounded by the 3′ and 5′ untranslated regions (UTRs), one 5′ cap, and a terminal polyadenylate tail. The mRNA vaccine is administered and then translated into the cell's ribosomes to produce the target antigen (Kairuz *et al*.,2022). Even while an individual messenger RNA molecule only encodes one particular antigenic substance, it can be translated to produce a significant amount of that antigen (Lui *et al*., 2019). RNA vaccines are evolving rapidly and offer several benefits, including safety due to RNA's non-contagious nature and its breakdown by cellular functions, as well as eliminating the risk of infection or insertional mutagenesis (Pardi *et al.,*2018).

**Delivery methods**

The choice of the right delivery route and technique has a significant impact on an aquaculture vaccine's efficacy. The successful administration of vaccination is just as important as its design. Therefore, in aquatic species, accurate administration is essential to attaining maximum immunological responses (Siskind et al.,1969). Throughout the research and development phase of aquaculture vaccinations, specific vaccine delivery strategies are required due to several factors, including vaccination technology, the species and stage of reproduction of the organism, knowledge of the pathogen's characteristics and infection pathways, and financial considerations (Mondal and Thomas, 2022). The main immunization delivery methods used in the aqua-culture field today are as follows:

**Vaccination via injection.**

The majority of aquaculture vaccinations are administered intramuscularly or intraperitoneally via injection. This technique is vital for guaranteeing precise and regulated vaccination antigen delivery within the organism that is targeted (Tammas *et al*.,2024). Among the various methods of administration, intraperitoneal injections offer the most effective and durable immunization (Dalmo *et al*.,2016). Injection vaccination effectively bypasses natural barriers that could prevent the vaccine from being distributed and absorbed uniformly, allowing for the precise administration of vaccine antigens in precise quantities. This method also facilitates the incorporation of adjuvants, which enhance the immunization process (Assefa et al., 2018).

**Vaccination via immersion**

During immersion vaccination, aquatic species are submerged in a specially prepared vaccine solution, allowing antigens to be absorbed through the mucosal surfaces of their skin, gills, gut, and nasal passage (Muñoz-Atienza *et al.,*2021). This strategy simulates natural infection pathways and builds an effective defensive network against common aquatic pathogens by promoting the immune system's mucosal and systemic responses.

**Oral vaccination**

Oral administration of aquaculture vaccines can be accomplished by either directly adding or combining vaccination antigens with feed (Mondal et al., 2022). With this method, vast numbers of animals can be mass vaccinated without requiring specific treatment, thereby reducing labor costs and minimizing stress, which enhances the welfare of organisms (Lillehaug.,2014). Additionally, it is adaptable for animals of all sizes, making it particularly suitable for applications like vaccinating fish fry that require prompt immunization (Wang et al., 2020**).**

**Innovations in vaccine delivery**

**Nanoparticle delivery**

A nanoparticle is a very small particle that can have a size of 1 to 100 nm, which provides a flexible way to administer vaccines (Zhao *et al.,*2014). Currently, nanopolymers are the most widely employed class of nanoparticles (NPs) in aquaculture vaccinations due to their biological compatibility and ability to degrade within the hosts. Lipid-based nanoparticles, which also serve as an adjuvant to produce a polymer for targeted antigen delivery, are an efficient means of delivering nanoparticles and enhancing immune responses. This tactic is commonly referred to as immunostimulating complexes (ISCOMs). Saponins and lipids like cholesterol or phospholipids combine to form these complexes, which self-assemble into structures about 40 nm in size (Vinay *et al*.,2018).

**Microencapsulation**

In the aquaculture sector, microencapsulation has become a widely used technology to manufacture potent oral vaccinations (Radhakrishnan *et al.,*2023). This methodology includes the application of polymers, which might be synthetic or natural. Historically, chitosan, alginate, and PLGA polymers have been used. The adjuvant features of nanoparticles enhance immune function while enabling the extremely selective and targeted delivery of antigens within hosts (Jazayeri *et al*.,2021). Another intriguing and very promising encapsulation technique being researched in the field of oral vaccination for aquaculture is bioencapsulation. Introducing living things as biological carriers to deliver vaccination antigens is a unique strategy that often uses organisms that are fed to aquatic species for nutrition (Ma *et al*.,2020). The bioencapsulated antigens are absorbed entirely upon ingestion of these organisms, hence promoting the development of immune responses on the mucosa and systemic levels (Radhakrishnan *et al*., 2023).

**Case studies**

Ravid-Peretz *et al*., 2019 described a vaccine developed against *Mycobacterium marinum*, the primary etiological agent of mycobacteriosis in European sea bass, targeting bacterial disease. The avirulent strain of *M. marinum* was heat-inactivated for vaccination, combined with 70% Montanide™ ISA 760 VG adjuvant, with a booster administered 30 days post-vaccination. The challenge utilized a virulent strain of *M. marinum*. The only group to exhibit a distinct IgM response was the one that got a single adjuvanted vaccine. Pridgeon *et al*.,2011 described attenuated vaccines developed against *Streptococcus iniae* for Nile Tilapia (*Oreochromis niloticus*). A formulation cultivated on novobiocin medium was administered through intraperitoneal (IP) injection, achieving relative percent survival (RPS) rates of 100% and 79–100% against parental and heterologous strains, respectively. When delivered via bath, the vaccine produced an RPS of 86% against the homologous strain. High mortality rates of 80–100% for IP injections and 64% for immersion administration were observed in the unvaccinated controls. Smage *et al*., 2018 formulated a vaccine against *Tenacibaculum finnmarkense* in Atlantic Salmon (*Salmo salar*) using a 0.4% formalin-inactivated HFJT strain combined with mineral oil as an adjuvant. Fish at the parr stage received intraperitoneal (IP) injections of bacterin at concentrations of 1× and 0.06×. After smoltification, all groups were challenged with either the homologous HFJT strain or the heterologous Tsp.2 strain. Although the higher concentration induced a stronger antibody response at 8 and 12 weeks post-vaccination, it did not provide adequate protection for the fish. The HFJT strain proved to be highly pathogenic, resulting in 90–100% mortality, while surprisingly, controls challenged with Tsp.2 exhibited lower mortality rates (30–65%) compared to vaccinated fish (25–84%) in three out of four trials, regardless of vaccine concentration. Xu et al.,2020 evaluated the effectiveness of different doses and schedules of a pcDNA3.1-IAg52b plasmid DNA vaccine against *Ichthyophthirius multifilis* in channel catfish. Six groups were tested: 10 μg, 20 μg, two doses of 10 μg, a mock control, a positive control with live theronts, and a non-vaccinated control. The fish immunized with 20 μg or two shots of 10 μg had considerably greater anti-Ich antibody concentrations and survival rates (35.6% and 48.9%, respectively) in comparison to the sham controls (0%), which received a dose of 10 μg.

**Conclusion**

The immune system is a network within an organism that detects a broad range of agents, from viruses to parasitic worms, protects against diseases. Understanding the immune system of fish and developing effective vaccination strategies are critical for ensuring fish health and sustainability in aquaculture. As pathogens continue to evolve, ongoing research and innovation in vaccine technology and delivery methods will be vital in enhancing disease resistance in aquatic species. Further studies will provide deeper insights into host-pathogen interactions and the development of novel vaccines to protect fish against various types of pathogens.

**References**

Assefa, A., & Abunna, F. (2018). Maintenance of fish health in aquaculture: review of epidemiological approaches for prevention and control of infectious disease of fish. *Veterinary medicine international*, *2018*(1), 5432497.

Bhavsar, A.P., Guttman, J.A. and Finlay, B.B., 2007. Manipulation of host-cell pathways by bacterial pathogens. *Nature*, *449*(7164), pp.827-834.

Blom, A.M., Hallström, T. and Riesbeck, K., 2009. Complement evasion strategies of pathogens—acquisition of inhibitors and beyond. *Molecular immunology*, *46*(14), pp.2808-2817.

Celli, J. and Finlay, B.B., 2002. Bacterial avoidance of phagocytosis. Trends in microbiology, 10(5), pp.232-237.

Collins, F. M. (1974). Vaccines and cell-mediated immunity. *Bacteriological Reviews*, *38*(4), 371-402.

Czochor, J., & Turchick A. (2014). Introduction. Vaccines. *The Yale Journal of Biology and Medicine*, *87*(4), 401-402.

Dalmo, R., Bøgwald, J., & Tafalla, C. (2016). Adjuvants and delivery methods: current and novel. *Fish vaccines*, 75-103.

Desmettre, P., & Martinod, S. (1997). Research and development. *Veterinary Vaccinology*, 175-194.

Dungu, B. K. (2011). *Assessment of vaccine delivery systems and their impact on the enhancement of immunogenicity, potency and safety of specific livestock vaccines used in South Africa*. University of Pretoria (South Africa).

Finlay, B.B. and McFadden, G., 2006. Anti-immunology: evasion of the host immune system by bacterial and viral pathogens. *Cell*, *124*(4), pp.767-782.

Gao, L.Y. and Kwaik, Y.A., 2000. The modulation of host cell apoptosis by intracellular bacterial pathogens. *Trends in microbiology*, *8*(7), pp.306-313.

Hansson, M., Nygren, P. A. K., & Sta˚ hl, S. (2000). Design and production of recombinant subunit vaccines. *Biotechnology and applied biochemistry*, *32*(2), 95-107.

Hølvold, L. B., Myhr, A. I., & Dalmo, R. A. (2014). Strategies and hurdles using DNA vaccines to fish. *Veterinary research*, *45*, 1-11.

Jazayeri, S. D., Lim, H. X., Shameli, K., Yeap, S. K., & Poh, C. L. (2021). Nano and microparticles as potential oral vaccine carriers and adjuvants against infectious diseases. *Frontiers in pharmacology*, *12*, 682286.

Johnson, L.R., 2008. Microcolony and biofilm formation as a survival strategy for bacteria. *Journal of theoretical biology*, *251*(1), pp.24-34.

Joo, H.S., Fu, C.I. and Otto, M., 2016. Bacterial strategies of resistance to antimicrobial peptides. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1695), p.20150292.

Kairuz, D., Samudh, N., Ely, A., Arbuthnot, P., & Bloom, K. (2022). Advancing mRNA technologies for therapies and vaccines: An African context. *Frontiers in Immunology*, *13*, 1018961.

Kaparakis-Liaskos, M. and Ferrero, R.L., 2015. Immune modulation by bacterial outer membrane vesicles. *Nature Reviews Immunology*, *15*(6), pp.375-387.

Khan, R.A., 2012. Host‐Parasite Interactions in Some Fish Species. *Journal of parasitology research*, *2012*(1), p.237280.

Kurath, G. (2008). Biotechnology and DNA vaccines for aquatic animals. *Revue scientifique et technique-Office international des épizooties*, *27*(1), 175.

Levine, M. M., & Sztein, M. B. (2004). Vaccine development strategies for improving immunization: the role of modern immunology. *Nature immunology*, *5*(5), 460-464.

Lieschke, G.J. and Trede, N.S., 2009. Fish immunology. *Current Biology*, *19*(16), pp.R678-R682.

Lillehaug, A. (2014). Vaccination strategies and procedures. *Fish vaccination*, 140-152.

Liu, M. A. (2019). A comparison of plasmid DNA and mRNA as vaccine technologies. *Vaccines*, *7*(2), 37.

Ma, Y., Liu, Z., Hao, L., Wu, J., Qin, B., Liang, Z., ... & Cao, J. (2020). Oral vaccination using Artemia coated with recombinant *Saccharomyces cerevisiae* expressing cyprinid herpesvirus-3 envelope antigen induces protective immunity in common carp (Cyprinus carpio var. Jian) larvae. *Research in veterinary science*, *130*, 184-192.

Mokhtar, D.M., Zaccone, G., Alesci, A., Kuciel, M., Hussein, M.T. and Sayed, R.K., 2023. Main components of fish immunity: An overview of the fish immune system. *Fishes*, *8*(2), p.93.

Mondal, H. and Thomas, J., 2022. A review on the recent advances and application of vaccines against fish pathogens in aquaculture. *Aquaculture international*, *30*(4), pp.1971-2000.

Moran, A.P., Prendergast, M.M. and Appelmelk, B.J., 1996. Molecular mimicry of host structures by bacterial lipopolysaccharides and its contribution to disease. *FEMS Immunology & Medical Microbiology*, *16*(2), pp.105-115.

Muñoz-Atienza, E., Díaz-Rosales, P., & Tafalla, C. (2021). Systemic and mucosal B and T cell responses upon mucosal vaccination of teleost fish. *Frontiers in Immunology*, *11*, 622377.

Palmer, G.H., Bankhead, T. and Seifert, H.S., 2016. Antigenic variation in bacterial pathogens. *Virulence Mechanisms of Bacterial Pathogens*, pp.445-480.

Pardi, N., Hogan, M. J., Porter, F. W., & Weissman, D. (2018). mRNA vaccines—a new era in vaccinology. *Nature reviews Drug discovery*, *17*(4), 261-279.

Pridgeon, J. W., & Klesius, P. H. (2011). Development and efficacy of a novobiocin-resistant *Streptococcus iniae* as a novel vaccine in Nile tilapia (*Oreochromis niloticus*). *Vaccine*, *29*(35), 5986-5993.

Radhakrishnan, A., Vaseeharan, B., Ramasamy, P., & Jeyachandran, S. (2023). Oral vaccination for sustainable disease prevention in aquaculture—an encapsulation approach. *Aquaculture International*, *31*(2), 867-891.

Rauta, P.R., Nayak, B. and Das, S., 2012. Immune system and immune responses in fish and their role in comparative immunity study: a model for higher organisms. *Immunology letters*, *148*(1), pp.23-33.

Ravid-Peretz, S., Colorni, A., Sharon, G., & Ucko, M. (2019). Vaccination of European sea bass *Dicentrarchus labrax* with avirulent *Mycobacterium marinum* (iipA:: kan mutant). *Fish & Shellfish Immunology*, *90*, 317-327.

Reyes-Sandoval, A., & Ertl, H. C. (2001). DNA vaccines. *Current molecular medicine*, *1*(2), 217-243.

Shoemaker, C. A., Klesius, P. H., Evans, J. J., & Arias, C. R. (2009). Use of modified live vaccines in aquaculture. *Journal of the World Aquaculture Society*, *40*(5), 573-585.

Siskind, G. W., & Benacerraf, B. (1969). Cell selection by antigen in the immune response. *Advances in immunology*, *10*, 1-50.

Småge, S. B., Frisch, K., Vold, V., Duesund, H., Brevik, Ø. J., Olsen, R. H., ... & Nylund, A. (2018). Induction of tenacibaculosis in Atlantic salmon smolts using *Tenacibaculum* *finnmarkense* and the evaluation of a whole cell inactivated vaccine. *Aquaculture*, *495*, 858-864.

Tammas, I., Bitchava, K., & Gelasakis, A. I. (2024). Transforming aquaculture through vaccination: A review on recent developments and milestones. *Vaccines*, *12*(7), 732.

Tlaxca, J. L., Ellis, S., & Remmele Jr, R. L. (2015). Live attenuated and inactivated viral vaccine formulation and nasal delivery: potential and challenges. *Advanced drug delivery reviews*, *93*, 56-78.

Ulmer, J. B., Mason, P. W., Geall, A., & Mandl, C. W. (2012). RNA-based vaccines. *Vaccine*, ***30***(30), 4414-4418.

Vinay, T. N., Bhat, S., Gon Choudhury, T., Paria, A., Jung, M. H., Shivani Kallappa, G., & Jung, S. J. (2018). Recent advances in application of nanoparticles in fish vaccine delivery. *Reviews in Fisheries Science & Aquaculture*, *26*(1), 29-41.

Wang, Q., Ji, W., & Xu, Z. (2020). Current use and development of fish vaccines in China. *Fish & shellfish immunology*, *96*, 223-234.

Xu, D. H., Zhang, D., Shoemaker, C., & Beck, B. (2020). Dose effects of a DNA vaccine encoding immobilization antigen on immune response of channel catfish against *Ichthyophthirius multifiliis*. *Fish & Shellfish Immunology*, *106*, 1031-1041.

Zhao, L., Seth, A., Wibowo, N., Zhao, C. X., Mitter, N., Yu, C., & Middelberg, A. P. (2014). Nanoparticle vaccines. *Vaccine*, *32*(3), 327-337.

Zhou, B., Gao, Y., Zhang, P. and Chu, Q., 2021. Acquired resistance to immune checkpoint blockades: the underlying mechanisms and potential strategies. *Frontiers in Immunology*, *12*, p.693609.