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Sustainable Disease Management in Aquaculture: Analyzing Pathogens, Treatments, and Control Strategies

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Abstract

Aquaculture is an indispensable component of the rapidly growing global seafood market, although it encounters several challenges concerning the management of disease outbreaks impacting fish health and farm productivity. This thesis examines the key bacterial, viral, parasitic and fungal pathogens of aquaculture with respect to associated environmental and management risk factors which may exacerbate disease transmission in intensive culture systems. The study reviews existing treatment methods — relevant to antibiotics vaccination, probiotics, and herbal treatments — and measures both the efficacy and viability of each.

The methodology involved a mixed-methods approach including a literature review and analysis of case studies pertaining to disease outbreaks and management practices in the different aquaculture systems. The confirmatory findings reveal a high risk, potentially leading to disease outbreaks with conditions such as high stocking density, poor water quality and lack of biosecurity measures that favor pathogens amplification. Antimicrobials continue to be used but cause AMR that has become a problem for environment and public health. Oral vaccines, probiotics and better water resource management are alternative approaches with potential to reduce antibiotic usage in fish farming while increasing the immunocompetency of fish and have less environmental impacts.

The study suggests that the transition to integrated disease management approaches—through the integration of robust biosecurity practices, alternative treatment methods and environmental health monitoring—can facilitate healthy fish and resilience in farms.

These recommendations aim to support the aquaculture industry in adopting practices that are both economically viable and ecologically sustainable, ensuring the long-term success of fish farming in meeting global food security needs.

Összefoglalás

Az akvakultúra a gyorsan növekvő globális tenger gyümölcsei piacának nélkülözhetetlen eleme, de napjainkban számos kihívással néz szembe a halak egészségét és a gazdaságok termelékenységét befolyásoló járványkitörések kezelése terén. A disszertáció az akvakultúra legfontosabb bakteriális, vírusos, parazita és gombás kórokozóit vizsgálja a kapcsolódó környezeti és gazdálkodási kockázati tényezők szempontjából, amelyek súlyosbíthatják a betegségek terjedését intenzív tenyésztési rendszerekben. A tanulmány áttekinti az elérhetőkezelési módszereket – amelyek az antibiotikum-adagolás, a probiotikumok és a gyógynövényes kezelések szempontjából relevánsak –, és mérik mindegyikük hatékonyságát és életképességét.

A módszertan vegyes módszereket alkalmazott, beleértve a szakirodalom áttekintését és a különböző akvakultúra-rendszerek betegségkitöréseire és kezelési gyakorlataira vonatkozó esettanulmányok elemzését. A megerősítő eredmények magas kockázatot tárnak fel, amely potenciálisan betegségek kitöréséhez vezethet olyan körülmények között, mint a nagy állománysűrűség, a rossz vízminőség és a kórokozók felszaporodását elősegítő biológiai biztonsági intézkedések hiánya. Az antimikrobiális szerek továbbra is használatosak, de antibiotikum rezisztenciát okoznak, amely napjainkra komoly környezet- és közegészségügyi problémává vált. Az orális vakcinák, a probiotikumok és a jobb vízkészlet-gazdálkodás olyan alternatív megközelítések, amelyek csökkenthetik az antibiotikum-felhasználást a haltenyésztésben, miközben növelik a halak immunkompetenciáját, és kevésbé károsak a környezetre.

A tanulmány azt sugallja, hogy az integrált betegségkezelési megközelítésekre való áttérés – a robusztus biológiai biztonsági gyakorlatok, az alternatív kezelési módszerek és a környezeti egészségi monitorozás integrálása révén – elősegíti az egészséges halak ellenálló képességét.

Ezen ajánlások célja, hogy támogassák az akvakultúra-ipart a gazdaságilag életképes és ökológiailag fenntartható gyakorlatok elfogadásában, biztosítva a haltenyésztés hosszú távú sikerét a globális élelmezésbiztonsági szükségletek kielégítésében.

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Introduction

Background of Aquaculture and Fish Health

Aquaculture is now one of the fastest-growing food production sectors worldwide and has played a major role in increasing global seafood supplies. Aquaculture provides more than 50% of the fish consumed all over the globe these days according to Food and Agriculture Organization (FAO). The trend towards aquaculture reduces the pressure placed on overfished wild stocks and provides reliable protein for an increasing population (FAO 2020). Even though aquaculture has advantages, it also brings in new problems – maintaining the fish healthy in a high-density farming environment. Extensive aquaculture systems, where fish are farmed in large numbers, but within a confined area which increases risk of disease spread. Because fish are crowded together, pathogens can easily move from one to another; meanwhile, things like poor water quality and temperature changes make the fish even less resistant to other diseases. Consequently, the outbreaks of diseases may cause economic losses; high mortality and low-quality fish which threaten the sustainability and profitability of aquaculture. [3;9]

Importance of Disease Management in Aquaculture

Effective disease management is essential for sustaining productivity in aquaculture and ensuring the health of farmed fish. Disease outbreaks caused by bacteria, viruses, parasites, and fungi are common in aquaculture and can have devastating impacts if not properly controlled. Rapidly spreading Bacterial diseases such as Vibriosis, viral infection such as Infectious Salmon Anemia (ISA), and parasitic infestations like sea lice may result in high mortality rates [2]. Although antibiotics and chemical agents are frequently administered to treat such diseases, their overutilization has resulted in antimicrobial resistance (AMR), posing a major global concern for aquaculture as well as human health [4]. Given the increasing use of aquaculture disease management practices, away from AMR, their environmental effects are an emerging concern. The environmental picture is further complicated by the release of active pharmaceutical ingredients such as antibiotics, antiparasitic agents, and other chemicals into water systems with adverse impacts on non-target organisms and ecosystems through toxic residues remaining in the environment. Hence, sustainable disease management practices are urgently needed to align the economic objectives of aquaculture with environmental stewardship [5].

Research Problem

The main difficulty aquaculture managers currently face with disease management is finding control methods that are effective but do not adversely impact the environment or promote AMR. Antibiotics are a traditional treatment, and they work for a limited time but not in the long term because of their negative environmental impact and contribution to resistant pathogens. Additionally, with emerging diseases and climate change affecting environmental conditions aquaculture farms are having more difficulty keeping their fish healthy and minimizing outbreaks. Abstract Acknowledging the pressing necessity of sustainable disease management strategies in aquaculture, this research includes alternative treatment and prevention methods. This study attempts to contribute towards a disease management framework for aquatic systems that integrates fish health with ecological sustainability by analyzing current practices and exploring innovations in biosecurity, vaccination, probiotics and herbal treatment. [4;9]

Objectives of the Study

This thesis aims to address sustainable aquaculture disease management approaches, specifically targeting productivity, fish health, and environmental consequences. Through a comparison of standard and alternative disease management practices, the study seeks to inform strategies that lower antibiotic use, improve biosecurity and facilitate sustainable farming.

Literature Review

Emerging diseases in aquaculture, represents a major challenge for fish welfare as well as the sustainable productivity of farms and this industry overall. This chapter discusses the key pathogens affecting aquaculture including bacteriological, virological, parasitic and viral diseases. The book chapters present sections on the major pathogens, their symptoms, routes of transmission and challenges to treatment and control.

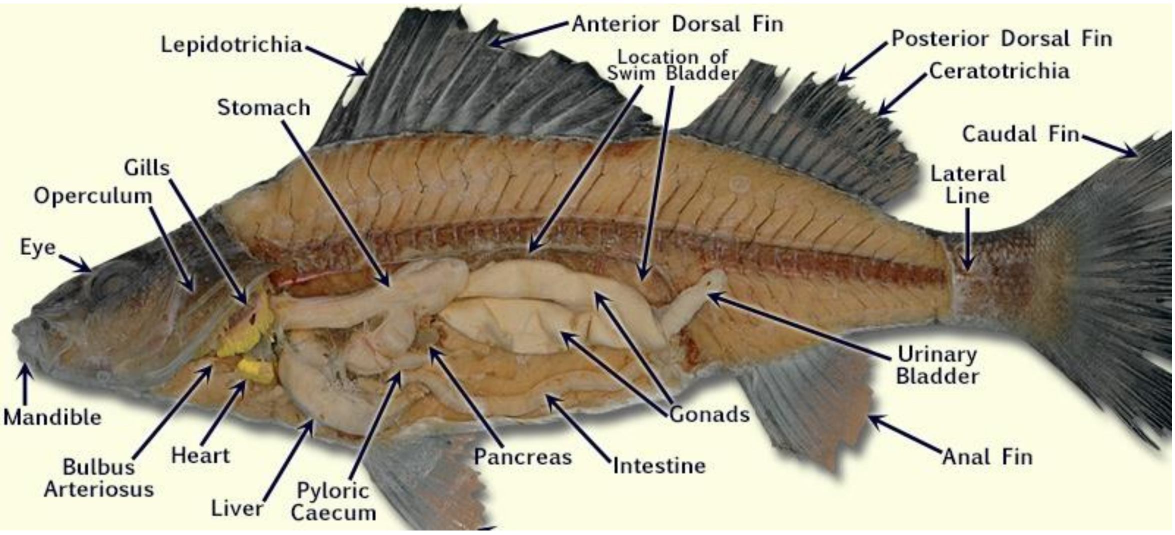

Figure 1: Anatomy of perch

Bacterial Diseases in Aquaculture

Bacterial infections are among the most frequent and economically damaging diseases in aquaculture. Intensive farming practices, characterized by high stocking densities and sometimes suboptimal water quality, create favorable conditions for bacterial growth and spread [2].

Common Bacterial Pathogens

- **Vibrio spp.**: Vibrio bacteria are one of the most common causes of bacterial disease in marine aquaculture, affecting species like shrimp, tilapia, and salmon. Vibriosis, caused by *Vibrio anguillarum*, *Vibrio harveyi*, and other species, leads to symptoms such as skin ulcers, fin erosion, and systemic infections that cause high mortality [2]. These infections are exacerbated by poor water quality, which compromises the immune systems of fish, increasing susceptibility to infections [3].
- **Aeromonas salmonicida**: Known for causing Furunculosis, *Aeromonas salmonicida* primarily affects salmonids. Furunculosis causes open ulcers, lethargy, and swollen spleens, leading to high mortality rates if not managed effectively [7]. Although antibiotics can be used to treat these infections, their overuse has led to AMR, highlighting the need for alternative strategies.
- **Streptococcus iniae**: This pathogen is common in tilapia and other freshwater species and is associated with septicemia, erratic swimming, and exophthalmia. Streptococcal infections can result in significant production losses and are often treated with antibiotics, though AMR has become an increasing concern [10].
- **Flavobacteria:** The Flavobacteria are primarily responsible for most bacterial pathogenic diseases in aquaculture, causing columnaris disease (*Flavobacterium columnare*) and bacterial coldwater disease (BCWD) (*Flavobacterium psychrophilum*), respectively. *F. columnare* is mainly caused on warmwater species including catfish and tilapia and typically causes skin lesions and gill necrosis, whereas *F. psychrophilum* infections are most prevalent in salmonids, causing systemic disease and skeletal deformities, particularly at colder temperatures [10;13]. Aquaculture environments are especially vulnerable because these diseases thrive under stressful conditions such as poor water quality, high stocking densities, and fluctuating temperatures. Over the years the traditional treatment has depended on antibiotics, however; overusing antibiotics has resulted in the emergence of antimicrobial resistance (AMR) in the flavobacterial strains making them ineffective and posing environmental challenges. [14;15;16]

- **Mycobacterium:** *Mycobacterium* spp. are opportunistic pathogens that present an important challenge to aquaculture, with the most prominent species being *Mycobacterium marinum*, *Mycobacterium fortuitum*, and *Mycobacterium chelonae*. Mycobacteriosis, a chronic infection in many different species of freshwater and marine fish, is caused by these bacteria. Granulomatous lesions in internal organs, skin ulcers, and emaciation characterize mycobacteriosis, which ultimately results in slowed growth rates and high mortality in infected fish populations. [10;17]

Treatment Challenges and Management Approaches

Antibiotics are widely used to control bacterial diseases in aquaculture. Nevertheless, the overuse of antibiotics has caused AMR which reduces the effect of these drugs and is dangerous to human and animal health [4]. To address this issue, sustainable treatment methods are gaining attention, such as vaccination and probiotics. Probiotics promote the growth of beneficial bacteria in the fish intestines, which can decrease pathogenic bacteria and strengthen immune responses [5]. Vaccines are also used as prevention especially for Furunculosis and Vibriosis and could remain for long period with no adverse impacts even when compared to antibiotics [2].

Viral Diseases in Aquaculture

Viruses are highly infectious pathogens that can lead to rapid and severe outbreaks in aquaculture. Unlike bacterial infections, viral diseases often lack effective treatment options, making prevention and biosecurity essential in managing viral threats [10].

Notable Viral Pathogens

- **Infectious Salmon Anemia Virus (ISAV)**: ISAV is a significant pathogen in salmon farming, particularly in countries like Norway and Chile, where salmon aquaculture is economically important. ISAV causes Infectious Salmon Anemia (ISA), which is characterized by pale gills, hemorrhaging, and lethargy. The virus spreads rapidly in high-density systems and has caused severe economic losses in affected regions [10].
- **Viral Hemorrhagic Septicemia Virus (VHSV)**: VHSV primarily affects freshwater and marine fish in temperate climates, such as trout and salmon. VHSV causes hemorrhaging in internal organs and high mortality rates in severely infected populations. Temperature changes and environmental stressors, such as poor water quality, often exacerbate VHSV outbreaks [1].
- **Infectious Haematopoietic Necrosis (IHN)**: It is a devastating viral disease of freshwater fish; salmonids including rainbow trout (*Oncorhynchus mykiss*) and many species of Pacific salmon (*Oncorhynchus* spp.) are especially susceptible. The disease is caused by the infectious haematopoietic necrosis virus (IHNV), which is a member of the family Rhabdoviridae. IHN primarily occurs in aquaculture facilities and natural environments in temperate regions. Disease incidence peaks in the 8–15°C water temperature range, optimal for viral replication. Clinical signs of IHN include blackened pigmentation, lethargy, uncoordinated swimming, exophthalmia and hemorrhaging in internal organs and musculature. Mortality rates are fatal as outbreaks can kill 90% of juvenile fish. The transmission route is horizontal via an exposure through the environment that is directly or indirectly contact with infected fish or contaminated apparatus, and under favorable conditions the virus can survive in water for long periods. Vertical transmission, in which a virus infects embryos via eggs, also is an important route of dissemination within aquaculture systems. Tools for the early molecular diagnostic detection of the virus, such as RT-PCR, along with strict biosecurity protocols, have been critical for containment of the disease and aquaculture health. [10;18;19]

- **Koi Herpes Virus**: Koi Herpes Virus (KHV) is an infectious viral disease of koi carp (*Cyprinus carpio koi*). Cyprinid Herpesvirus-3 (CyHV-3), a member of the Alloherpesviridae family, is responsible for the disease and represents an important threat to the global carp aquaculture and ornamental fish industries. Evidence suggests that KHV outbreaks are most prevalent in water temperatures between 18°C and 28°C, with infected fish showing clinical signs associated with the disease such as lethargy, sunken eyes, skin discoloration, gill necrosis, and an increased production of mucus. Mortality can be devastating, approaching 100% under ideal circumstances [20]. Horizontal transmission occurs through direct contact within infected fish, as well as contaminated water or other equipment. Stressors like bad water quality, crowding, and temperature changes make outbreaks worse. Latent infections are also possible, enabling asymptomatic carriers to spread the virus under stress, complicating disease control efforts [21].

Figure 2: KHV causing necrotic lesions on the gills

- **Epizootic Haematopoietic Necrosis (EHN)**: It is a viral disease caused by the epizootic haematopoietic necrosis virus (EHNV), an iridovirus which is highly lethal. EHN is a severe disease that predominantly infects freshwater fish species such as redfin perch (*Perca fluviatilis*) and rainbow trout (*Oncorhynchus mykiss*), it is associated with rapid disease progression and high mortality rate especially among juvenile fish. Clinical signs including lethargy, darkened color, abdominal distention, bleeding, necrosis in hematopoietic tissue of kidney and spleen. EHNV is a resistant virus that can persist in water and on contaminated equipment for long periods of time, leading it to spread in aquaculture systems. Horizontal transmission happens through waterborne exposure to infectious fish, fomites, or contaminated water, and the disease is worsened by environmental stressors i.e. poor water quality and temperature flush. Management of temperate aquaculture systems is made particularly challenging by the fact that outbreaks are most conducive to water temperatures between 12 °C and 20 °C. [10;22]
- **Tilapia Lake Virus (TiLV)**: TiLV is an emerging viral threat in tilapia aquaculture, impacting farms across Asia, Africa, and Latin America. TiLV can lead to mortality rates as high as 90% in infected populations, with symptoms including skin lesions, abnormal swimming, and lethargy. Biosecurity practices are currently the primary method for preventing TiLV spread, as there is no effective antiviral treatment or widely available vaccine [6].

Control Strategies and Preventive Measures

Due to limited antiviral treatments in aquaculture, viral diseases are primarily managed through preventive measures, such as vaccination and biosecurity. For some viral pathogens, there are vaccines available (e.g., ISAV); however, for newly emerging viruses such as TiLV, the development of a vaccine is still needed. Molecular diagnostic tools such as PCR are important for the early detection of the disease, allowing for rapid isolation of infected fish to prevent transmission and further spread [11]. To reduce the chance of viral disease emergence and outbreaks, biosecurity protocols such as disinfection of equipment/equipment, quarantining new stock and restricting access to some areas of the farm are important [3].

Parasitic and Fungal Infections

Parasitic and fungal infections are widespread in aquaculture and can lead to significant losses if not managed effectively. These infections are often linked to environmental stressors, such as poor water quality, which creates favorable conditions for parasite and fungal proliferation [2].

Key Parasitic Pathogens

- ***Ichthyophthirius multifiliis***: Known as white spot disease, this protozoan parasite affects freshwater species, including carp and tilapia. Infected fish exhibit white cysts on their skin, gills, and fins, leading to irritation, respiratory difficulties, and, eventually, death if left untreated. Common treatments include formalin and salt baths, although these can be stressful for fish and may be impractical in large-scale operations [10].

Figure 3: Ichthyophthirius multifiliis

- **Coccidia – Apicomplexans**: Coccidia (phylum Apicomplexa) are protozoan parasites that cause the disease coccidiosis in common aquaculture species such as tilapia, carp, and catfish. The intracellular parasites, which infect the gastrointestinal tract, can cause enteritis, weight loss, impaired growth rates, and in extreme cases high levels of mortality. Eimeria and Cryptosporidium are the most significant genera of coccidian parasites present in fish farms, whereby Eimeria affects mainly freshwater species [10;24]. Infections with coccidia are usually fecal-orally by oocysts shed with feces of infected fish into water and ingested by healthy fish. Infected fish droppings create conditions suitable for coccidia dissemination, particularly in aquaculture systems with poor water quality, high stocking densities, and/or inadequate hygiene. Most of the infections are subclinical, but can become serious during stress, resulting in considerable economic losses in production and ornamental fish. [25]

- **Flagellates**: *Hexamita truttae* is flagellated protozoan parasite well known in the farm in crossbred freshwater fish especially involving salmonid fishes such as trout. It is known to cause hexamitiasis, a disease affecting the gastrointestinal tract that results in emaciation, reduced growth, and pale fecal casts. In more severe cases, the infection can spread systemically, affecting organs such as the liver and kidney. Hexamitiasis is mostly found in overpopulated or unaided aquaculture systems, in these conditions fish health affected by stress and bad water quality. [10;27]

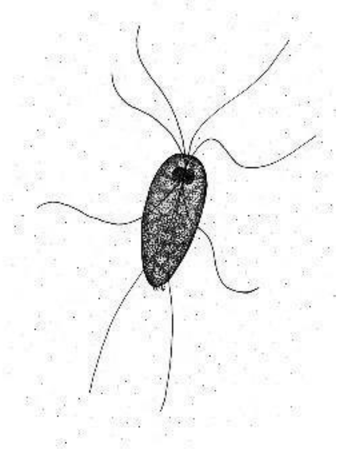

Figure 4: Hexamita

- **Myxoxporean**: Myxosporeans are a large group of protozoan parasites that belong to the phylum Myxozoa. These parasites are widespread in both marine and freshwater aquaculture, causing significant economic losses via infecting key species such as *Tetracapsuloides bryosalmonae* (causing proliferative kidney disease [PKD]) and *Myxobolus cerebralis* (causing whirling disease). This parasite affects the gills, and its main symptoms are deformities, erratic swimming, tissue necrosis, and reduced growth. Juvenile fish and intensive farming conditions can particularly increase mortality rates [10;25]. Transmission is usually (more on this soon) by a two-host life cycle, with fishes as the primary host and an invertebrate, such as oligochaete worms, as the intermediate host. This complex life cycle makes disease control challenging, as both hosts need to be managed to interrupt the cycle of transmission. The severity of myxosporean infections in a fish is consequently worsened by environmental stressors such as degraded water quality and the introduction of high stocking densities [27].

- ***Gyrodactylus* spp. and *Dactylogyrus* spp.**: These monogenean parasites affect the gills and skin of fish, primarily in freshwater systems. Heavy infestations cause respiratory distress and increased mucus production, weakening the fish and making them susceptible to secondary infections. Chemical treatments, like praziquantel, are effective but need to be used carefully to prevent environmental contamination. [10;23]
- **Trematodes**: So-called flukes are members of the class Trematoda—the parasitic flatworms. Aquaculture, especially in freshwater systems, has broad relevance, as they are important pathogens as well as a wide range of fish species. Trematodes, such as the eye fluke (*Diplostomum spathaceum*) and yellow grub (*Clinostomum complanatum*), are usually localized infections in the eyes, gills, and muscles. They can cause stunted growth, have implications for vision, reduce market value, and can be life-threatening in extreme cases [10]. Trematodes' life cycles generally involve an intermediate host (frequently snails) and a definitive host, usually birds or mammals. Cercariae released from infected snails can infect fish by ingestion, but also through direct penetration into fish tissue. While trematode infections are ubiquitous in aquaculture systems, certain environmental factors, such as stagnant water and high organic loads, promote snail populations [28]. Management of the trematodes largely depends on interrupting the parasite life cycle, which can be achieved by using chemicals, which reduce the snail populations with molluscicides, by introducing biological control agents such as snail-eating fish genotypes, and by improving water flow to reduce stagnant areas. Maintaining appropriate water quality and eliminating organic debris are essential specifics in the prophylaxis. Infected fish may be treated with antiparasitic agents—including praziquantel—but these must be used judiciously to prevent industry resistance development and environmental contamination. [23;29]

- **Cestodes**: Tapeworms or Cestodes: They are also classified as parasitic flatworms; however, they encompass a large variety of freshwater and marine fish species in aquaculture. Prominent examples of cestodes are Ligula intestinalis and Diphyllobothrium latum, which dwell within the intestines or body cavities of fish, leading to effects ranging from stunted growth, malnourishment, to organ failure or death. Certain species of cestode also represent zoonotic threats, and thus control of these infections in aquafeeds is important for the health of both fish and humans [10;28]. Cestodes generally have complex life cycles, with multiple hosts. The definitive hosts, usually birds or mammals, excrete eggs into the water, where they are ingested by crustaceans that serve as intermediate hosts. Fish become infected through predation on infected, crustaceans, which carry larval cestodes. Increased prevalence of cestode infections with high stocking densities, poor water quality, and definitive hosts presence in or near aquaculture facilities [30]. Cestode management strategies emphasize interrupting the parasite's life cycle. The first and foremost step is to control the population of intermediate and definitive hosts, such as preventing birds from accessing fishponds. Good feed hygiene also has an important role to play in reducing the chances of infection, as does improving water quality. Anthelmintic treatments for infected fish, e.g., praziquantel, can be performed, but they must be employed judiciously to avoid the development of paragonimiasis resistance and pollution of the environment. Sustainable practices range from keeping an eye on wild bird activity, to incorporating biosecurity measures that limit the spread of parasites. [23,29]

- **Nematoda**: Nematodes or roundworms are a group of parasitic worms commonly found in aquaculture that infects wide variety of fish species the most notable species *Anisakis simplex* and *Camallanus cotti*. Nematode infections can lead to weight loss, gastrointestinal damage and reduced growth rates in fish, while zoonotic species (e.g., Anisakis) represent a risk to human health when infected fish are eaten raw or undercooked [10;28]. The indirect life cycles of nematodes involve one or more intermediate hosts, such as crustaceans or mollusks, and one definitive host, usually either a bird or a marine mammal. Fish become infected by consuming intermediate hosts infected with the parasite. Management is therefore aimed at breaking this life cycle through the control of intermediate host populations and the access of definitive hosts (including birds) to aquaculture settings. Biosecurity measures, including proper water quality management and feed hygiene. Anthelmintics (e.g., levamisole) can be used to treat infected fish, although applications should be done carefully to avoid high environmental impact. [29]
- **Crabs (Sea lice)**: Sea Lice (*Lepeophtheirus salmonis* and *Caligus* spp.) are parasitic copepods and represent a major threat to marine aquaculture, such as salmon farming. These ectoparasites attach to the skin, fins and gills of fishes and cause lesions, stress, secondary infections and depress growth. High mortality occurs in case of heavily infected sea lice, making them an important economical and welfare problem in aquaculture. Sea lice are prevalent in crowded farming conditions, as high stocking densities enable their transmission. Hydrogen peroxide baths and emamectin benzoate are among clinical options, but resistance has been documented in some lice populations. Biological controls, such as cleaner fish such as wrasse and lumpfish, to take the place of pharmaceuticals are already established as effective sustainable options. The best way to control sea lice infestations is through integrated pest management (IPM) strategies combining biological controls, environmental management, and minimal use of chemicals. [10;31]

Figure 5: Salmon infected with Sea Lice

Fungal Infections in Aquaculture

Fish fungal infections are more rare than bacterial or viral diseases, but when fish health is stressed in a tank the possibility does exist. Saprolegnia species typically affect the skin and gills of fish and are seen when spawning or after transportation, sometimes called the cotton wool disease. Treatment is typically potassium permanganate or salt baths, however preventing this disease centers on water quality maintenance and stress reduction [1].

Management of Parasitic and Fungal Infections

Parasitic infections mainly are dampened down at source, they tend to occupy high organic matter environments. Biological controls, including the introduction of cleaner fish (decorative species of wrasse) that feast on parasite-infested flesh, appear to be a promising strategy for sustainably tackling this ongoing problem in salmon farms. Cleaner fish eat external parasites — for example, eating sea lice — lowering parasite burdens without the environmental risk of chemical treatments. They are environmentally friendly and reduce resistance problems compared to chemical treatments. [5;13]

Chemotherapeutic approaches for the control of coccidiosis are limited, and thus control in fish farms further relies on preventive measures. Better biosecurity measures — such as cleaning tanks often, lowering stocking densities and keeping environmental conditions optimal — are key to reducing the potential for infection. The administration of probiotics and immunostimulants has shown promise in ameliorating infection severity via augmenting the host immune response. In addition, research of species-specific vaccines targeting Eimeria species in aquaculture is still conducted and holds hope for sustainable disease control. [26]

Summary of Literature Review

Aquaculture is undoubtedly impacted the most by diseases caused by bacteria, viruses, parasites and fungi as highlighted in this literature review. In fish farms, bacterial pathogens mostly represented by Vibrio and Aeromonas species are the most common sources of infection, and their control must be cautious to prevent their development of AMR. ISAV and TiLV are viral infections for which no antiviral treatments exist, emphasizing biosecurity and vaccination as the only option to address this risk. Parasitic and fungal infections, although generally treated by improving water quality or using chemicals for disinfection still harm sustainable aquaculture practices as they can diminish production or lead to the loss of entire aquaculture stocks if not controlled. [2;3;10]

The revise highlights how an integrated disease management strategies that integrate biosecurity to prevent the introduction of livestock and poultry into new areas, sustainable treatment options, and sustain environmental surveillance would be helpful. This will ensure that our fish stay healthy in perpetuity and reduce the climate impact of aquaculture disease management strategies. These insights set the stage for the following chapters, which look at how treatment efficiency can be measured and ways to develop preventive sustainable fish health practices in aquaculture. [3;5;10]

Materials and Methods

The present study combines qualitative research with quantitative assessment of disease management to do so in aquaculture. Methods are literature review, case study analysis, and comparison of existing treatment methods to identify sustainable techniques to reduce disease risks while minimizing environmental effect.

Study Design

This research is an exploratory study to identify different disease management strategies in aquaculture and assess methods on their efficacies. The study design includes:

- Literature Review: Peer reviewed articles, industry reports and authoritative sources were systematically reviewed to establish the background knowledge around fish diseases, treatment and prevention.
- Case Study Analysis: Using selected case studies of disease outbreaks and management practices in aquaculture, this study provided insight into empirical methods used to deploy antibiotic use, vaccination, probiotics and biosecurity measures.
- Data Integration and Comparison: Data extracted from the literature and case studies were integrated to identify patterns and triangulate effectiveness of treatment or prevention strategy on fish health and environmental sustainability.

Data Collection

Methods: Data were collected from the secondary sources by reliable data bases and organizations including as follow:

- Academic Databases: Articles were acquired from PubMed, ScienceDirect and SpringerLink databases with a preference for studies in the past 15–20 years to reflect current trends in aquaculture disease management.
- Books about Fish Pathology
- Case Study Bias: case studies were selected based on the type of pathogen, aquaculture environment (e.g. freshwater vs marine) and the success of the management approach; Case studies involved specific notable outbreaks of some pathogens such as Infectious Salmon Anemia Virus (ISAV), and Tilapia Lake Virus (TiLV).

Sampling Methods

This study uses secondary data, and therefore, the sampling method was oriented towards obtaining representative literature and case studies including a wide range of aquaculture systems, fish species and disease management practices.

Inclusion Criteria

We included studies and reports if they:

- Cover disease control in aquaculture (therapy and prophylaxis)
- Presented numerical or descriptive data for the value of individual interventions such as antibiotics, vaccines, probiotics, or biosecurity.
- Addressing sustainability, especially from an environmental and antimicrobial resistance (AMR) perspective.

Exclusion Criteria

Excluded studies were:

- Insufficient detail on either method or results to enable reliable.
- Was conducted in a laboratory and not relevant for aquaculture.
- Limited to small-scale experiments lacking commercial aquaculture scalability evidence

Analytical Methods

We analyzed data from the literature review and case studies using descriptive, comparative techniques to evaluate the extent, efficacy and sustainability of disease management strategies.

Descriptive Analysis

Descriptive analysis was conducted to summarize the pathogens affecting aquaculture, management practices, and trends in disease prevention and treatment.

- Frequency Analysis: The number of case studies for bacterial, viral, parasitic and fungal diseases in aquaculture were tallied. Examples of this included analysis of the distribution and treatment of common pathogens.
- Trends: They were examined to determine how the adoption of sustainable management practices (i.e., probiotics and biosecurity protocols) modified industry trends in antibiotic use.

Comparative Analysis

A comparative analysis was performed with regards to the relative effectiveness, feasibility and sustainability of disease management strategies.

- Comparison of Effectiveness: Recovery rates, mortality reduction, and recurrence prevention were compared among different methods to manage the disease such as antibiotics, vaccines, probiotics and herbal remedies. This also facilitated comparing the advantages and disadvantages of each method.
- Environmental Impact Assessment: Environmental impact of treatment techniques was scrutinized especially for the methods based on chemical treatments. These risk-focused assessments were for water pollution, antimicrobial resistance, and non-target organism effects.

Case Study Synthesis

Synthesized case studies to experience practical implementation of several disease management practices. The integrated view of disease control in aquaculture was synthesized from the individual case studies, where key findings were collated with respect to best practices, challenges and lessons learnt.

Data Validity and Reliability

It was critical that the results would contain validity and reliability so that they were worthy of being used. These were the steps taken:

- Source credibility: Only high-quality sources were used (e.g. peer-reviewed journals, industry publications, reports from reputable organizations). Hence, it ensured credibility and quality collection of data.
- Cross Verification: Results from single studies were compared with data gathered through other methods to ensure similar findings and avoid biases. In cases of differences, preference was given to the most recent and largest studies.
- Limitations Acknowledgment: The inherent limitations of using secondary data, including potential publication bias and discrepancies in data reporting, were acknowledged. We kept these limitations in mind when interpreting the data and avoided overgeneralization of results.

Ethical Considerations

We used only secondary data in this research, so no direct interaction with animals or humans was involved; therefore, ethical issues are mitigated. Nevertheless, this was in a principled way:

- Properly attributing all sources and giving citation credit where due; respect for intellectual property rights.
- Not using nonpublic or proprietary data.
- Prioritizing sustainability-matching practices data under ethical and eco-responsibility in aquaculture

Summary

This chapter presented the aims and methods used to evaluate sustainable disease management in aquaculture: study design, data collection process, sampling criteria and analytical methods. This methodology identifies existing literature and case studies corresponding to effective/ sustainable disease prevention and control methods in aquaculture settings through a systematic review of the literature. This analysis is reported in the next chapter.

Results

The results of each level: prevalence and treatment efficacy from a literature review and biosecurity and other preventive measures from the case study are presented in this chapter. Real world contexts of different disease management strategies are depicted through specific case studies to showcase the outcomes and implications of the various approaches.

Overview of Findings

Results revealed that bacterial, viral and parasitic infections are the most important diseases affecting aquaculture with high burden such as Vibriosis representing the major cause for death whereas Infectious Salmon Anemia (ISA) is reported as of great concern and importance. While antibiotics are widely used to treat bacterial infections, in doing so they promote the emergence of antimicrobial resistance (AMR). The potential use of preventive methods such as biosecurity procedures, vaccination, and probiotic treatments have effective roles in limiting disease incidence as well as antibiotic dependence.

Pathogen Prevalence and Risk Factors

Parasitic Infections: Case Study of Sea Lice in Salmon Farms in Norway

Introduction Sea lice (*Lepeophtheirus salmonis*) are significant parasites relevant to salmon farming and impact farmers throughout the world especially in Norway. This parasite latches onto the skins of salmon and creates patches that are prone to bacterial infections, resulting in even greater mortality. Initially the control of sea lice was performed using chemical treatments such as hydrogen peroxide and organophosphates, however these chemicals were found to have been developed resistant generations in lice populations and thus were less effective [31].

In reply, Norwegian salmon farms turned to biological control: introducing cleaner fish — wrasse that eat sea lice. Cleaner fish were then introduced, resulting in a decrease of lice while not adding to custom resistance. This case study shows how biological controls can be a sustainable alternative to chemical treatments for aquaculture [10;31].

Bacterial Infections: Case Study of *Vibrio* in Shrimp Farming

The widespread and devastating nature of this bacterial pathogen is illustrated with a case study of *Vibrio* infections from shrimp farms in Southeast Asia. Massive outbreaks of vibriosis with high mortality rates (up to 50%) occurred on shrimp farms characterized by extremely high stocking density and poor management of water quality. The widespread use of antibiotics as a treatment entailed an overall decrease in the mortality; however, this led to the establishment of AMR [2]. In response, the farms used biosecurity, including better water filtration systems and quarantine methods, as well as adding probiotics for gut health and immunity. This reduction of *Vibrio* infections demonstrates that efforts to combine antibiotics with sustainable preventive approaches are key to success [3;5;32].

Viral Infections: Case Study of Infectious Salmon Anemia (ISA) in Chile

The ISA outbreak in the Chile's salmon industry illustrates the difficulties related to viral disease in the aquaculture sector. The ISA virus caused the disease ISA killed up to 90% in the affected farms and wiped out a billion dollars from the economy of the country. Specifically, the outbreak exposed several factors of Chilean aquaculture system that were potential risk factors: high density levels, lack of biosecurity measures, and farming in open water systems [10;33].

Chilean authorities reacted with strict biosecurity measures that required disinfection stations, to follow regulations regarding stocking densities and restricted the transport of fish between sites. Vaccination campaigns were also initiated, and the combination of biosecurity and vaccination enabled the industry to mitigate subsequent ISA outbreaks. As this case proves, there are no treatments against viral diseases like these; one can only prevent their outbreak with biosecurity and vaccination [33;34].

Treatment Efficacy and Sustainability

Antibiotics and AMR Concerns

Case study analyses reveal that AMR in aquaculture systems is largely driven using antibiotics which have been successful at controlling bacterial infections but are not sustainably used. In shrimp farms, overuse of antibiotics represented an alarming case: Vibrio isolates developed into resistant strains which could be difficult to control and enter the food chain, with serious implications for human health [4]. These all stress the necessity of restricting antibiotic use and adding complement methods to lower AMR hazards.

Vaccination: Insights from the ISA Case in Chile

In the case of viral diseases that cannot be treated with antibiotics, vaccination has been instrumental in reducing disease incidence. Vaccination greatly reduced the number of future outbreaks during Chile's response to ISA, as vaccinated salmon were found to have increased survival and decreased spread of virus compared to unvaccinated populations. These results corroborate with the vaccine's capability to control diseases like ISA where effective antiviral therapies are not available or means of protection tend to be prophylactic [9;33;34].

Probiotics and Herbal Remedies

Probiotics, in shrimps' example with Vibrio species type of farmer, and herbs that have been shown to enhance fish immunity and decrease pathogen loads (FDA, 2023). Introduction to the gut microbiota influences immune responses in fish and contributes to the development of resistance against infections. While not as instantaneous and action-oriented like antibiotics, probiotics manage to provide more sustainability at a very low cost on the environment while assisting in long-term transition to AMR mitigation. [5;32]

Preventive Measures and Biosecurity Outcomes

Biosecurity Protocols

In all the case studies biosecurity measures appeared to play an important role, especially on viral diseases like ISA and TiLV. The delineation of biosecurity zones, requirements for disinfection and transport restrictions were therefore essential to control the spread of infection in the ISA case in Chile. It improves health by preventing the introduction of pathogens, and thus reduces the demand for treatment, making it a sustainable form of disease management [3].

Water Quality Management

The Vibrio case study in shrimp farms exemplified the significance of water quality management. Increased disease incidence was attributed to poor water quality (high ammonia, low oxygen content). In an example of the impact of environmental management in disease prevention, the farms reduced pathogen loads and improved fish health by targeted improvements to filtration systems and monitoring of water quality parameters [3;32].

Summary of Results

The findings from these case studies and literature sources highlight the following:

1. AMR created by using antibiotics is a serious long term health hazard and has been shown to be an effective treatment method offering limited benefit in the short period of time but reducing the harmful consequences from abusing this treatment method.
2. Both for ISA and other viral infections, vaccination has demonstrated practical effectiveness in regions where biosecurity measures further reduce viral transmission.
3. Happily, probiotics and biological controls that boost immune response and resist the environmental costs of chemical treatments are becoming ever more promising alternatives.
4. These measures emphasize pathogen management through Biosecurity and Water Quality Management, which is a metaphor for preventative steps against pathogens that acts not by direct treatment but rather by ensuring the sustainability of well-being.

Our findings suggest that the implementation of integrated disease management strategies consisting of biosecurity, vaccination, probiotics and environmental management will help to reduce disease occurrence and thus improve fish health status whilst promoting more sustainable aquaculture. These insights serve as the foundation for recommendations in the next chapter Discussion and Conclusion.

Discussion and Conclusion

Analysis of Results

This multifactorial article reporting strategies used for disease management in aquaculture (with related case studies) depicts the complexity of controlling pathogens within high density farming systems. This chapter provides an overview of the results within the scope of sustainable aquaculture, treatment efficacy, preventive use and AMR and environmental impact.

Treatment Efficacy and Sustainability

The case studies show the scenario of severe bacterial infections in the world where antibiotics have been a first line treatment yet contributing to AMR. The Vibrio outbreak in the shrimp farms showed that, despite an initial quick reduction of bacterial load by using antibiotics, development of AMR makes further treatment difficult and represents a hazard to environmental and human health [4]. It highlights the urgent need to move away from antibiotic dependence, towards sustainable alternatives such as probiotics and vaccines.

Specifically, vaccination has been effective for controlling viral infections (ISA case in Chile). For example, vaccines impart prolonged protection to live animals against specific pathogens while avoiding the AMR risk and environmental pollutions associated with antibiotic treatment. Nonetheless, vaccines are not available for all pathogens or with good efficacy, but the situation is changing and more will need to be done especially for emerging diseases such as Tilapia Lake Virus (TiLV). This endorses a strategy of including vaccination, if possible, especially for viral pathogens with no other alternative treatment options. [6;34]

The Role of Probiotics and Herbal Remedies

As antibiotics are typically reserved for severe bacterial infections, probiotics and herbal components are now becoming a viable option to improve fish immunity and gut health without adverse effects. Reducing pathogen burden and enhancing fish health were achieved employing supplemental probiotics in the Vibrio case shrimp farming, providing a potentially sustainable approach for disease prevention. Although further research is warranted to determine dosing frequency and methods, the use of probiotics also presents an exciting option to help lessen reliance on antibiotics in aquaculture [5].

Preventive Measures: Biosecurity and Environmental Management

Biosecurity and environmental management as essential elements for sustainable control of aquaculture diseases. The highlight of biosecurity protocols that prevent the introduction and dissemination of pathogens in the ISA case studies in Chile and Vibrio in shrimp farms Biosecurity (e.g. equipment disinfection, restrictions on fish transport, and monitoring of water quality) is the primary preventative measure against disease outbreaks that eliminates or at least lessens the need for reactive treatments [3].

Ensuring proper water quality is critical to disease prevention, as stressed fish are incapable of exerting an immune response against pathogens, and shrimp farms experiencing Vibrio outbreaks (both epicenter sites) had poor environment conditions for which maintaining water quality would be a critical measure for Vibriosis control. So, the concomitant management of water quality with biosecurity practice can holistically provide fish resilience and small pathogen growth that facilitates sustainable aquaculture practices in the long run. [3;32]

Implications for Sustainable Disease Management

These results suggest that an integrated combination of preventive and curative methods is needed for sustainable disease management in aquaculture. Given the risks posed by AMR, the use of antibiotics should be restricted to life-threatening situations whereas, probiotics, vaccination and biosecurity should constitute the basis of disease interventions.

Sustainability increases the health of aquaculture and reduces the use of chemical agents in surrounding ecosystems leading to reduced water pollution. These strategies can help the aquaculture sector control disease threats as well as complement broader environmental and human health objectives. [3;4;5]

The Importance of AMR Mitigation

AMR affects human and animal health worldwide; it is not unique to aquaculture. Aquaculture overuse antibiotics as well, and some highly resistant bacteria may go into the food chain then flow to humans. The progress towards sustainability in animal production—exemplified by probiotics that eliminate AMR bacteria and vaccination preventing challenge engagement to keep healthy, long-lived animals—might be a driver of the tapering impulse for these products, thus marketing can potentially lessen antibiotic use dependence and AMR susceptibility. This change is vital for the future of aquaculture and public health. [3;4;5]

Recommendations for Disease Management in Aquaculture

The data supported the following recommendations for sustainable disease management in aquaculture:

1. Reduce Use of Antibiotics — only use antibiotics when necessary and whenever possible, use probiotics and herbal medicine to reduce the risk for AMR problems.
2. Adopt Biosecurity Measures: Enhance biosecurity measures within tilapia farms through disinfection protocols, isolation of new stock and regulated transportation of fish to reduce disease introduction.
3. Encourage Vaccination: Fund research in vaccines and promote their use (for viral diseases, where there is no treatment by other means).
4. Improve your water quality handling — regularly test for parameters and filter out contaminants that do not help the fish (stress will make your fishes lose their natural resistance to diseases).
5. Practice Integrated Disease Management (IDM): Use IDM as a comprehensive and integrated approach that includes biosecurity, vaccination, probiotics and environmental management according to the specific requirements or challenges of each aquaculture system.

Conclusion

The findings of this study emphasize the importance of sustainable approaches to disease management within aquaculture. The use of antibiotics, effective as it may be in the short term, however, has far-reaching effects since the development of AMR and degradation of environmental quality take time. Alternative measures such as probiotics, vaccination and biosecurity are promising options that both remediate these problems while ensuring fish health and farm productivity.

Integrated disease management makes sustainable aquaculture possible, reveals the research. This approach would allow the aquaculture industry to further develop sustainably to ensure global food security without undermining ecological integrity. The results of this study will enhance the information regarding sustainable aquaculture practices delivering practical insights on mitigating disease risk and boosting system resilience.

Summary

The same pressure is sensed in aquaculture, and with the fast-developing industry such skills or experience in providing farmers with adequate disease management methods focusing on fish health as well as environmental and economic sustainability remains scarcer. In this study we aimed to identify and assess sustainable aquaculture disease management strategies against bacterial, viral, parasitic, and fungal pathogens causing diseases in cultivated fish. Using a systematic literature review and case study analysis, this research provides examples of best practice strategies to reduce disease risk while minimizing the environmental pollutions as well as antimicrobial use.

Key Findings

1. Pathogen Prevalence: Bacteria, viruses, and parasites are the most common aquaculture disease-causing agents that can be made worse by high stocking densities; poor water quality; and insufficient biosecurity practices. The ISA outbreak in Chile, among other case studies reveal that the intensive farming systems are likely to provide favourable environments for spreading infections deleterious to fish health.
2. Antibiotic use and AMR challenges: To treat bacterial infections, antibiotics are heavily used globally but this overuse is an important cause of antimicrobial resistance (AMR) which represents a long-term challenge for aquacultures as well as public health. As seen in the Vibrio example at shrimp farming, high consumption and resultant resistance of bacteria to antibiotics can result in possessing resistant strains that are difficult to treat effectively or lead to overall greater risk for the environment.
3. Effectiveness of Sustainable Alternatives: Probiotics and vaccination have shown potential as sustainable alternatives to antibiotics, preventing infections effectively and without promoting AMR. While probiotics effectively improve gut health and immune responses (e.g., successful application in shrimp farms with Vibrio management), vaccines effectively decrease the incidence of viral diseases (e.g., ISA case in Chile).
4. Role of Biosecurity and Environmental Management: The measures taken to ensure the biosecurity, including quarantine and regulations over water quality, are essential in limiting the introduction and spread of pathogens. Case studies showed that biosecurity practices are effective in minimizing viral transmission in high-density environments and should be included as one of the sustainable outbreak management approaches.

Implications for Aquaculture Practices

These findings inform a move to integrated disease management in aquaculture. However, the harm against the environment has made sustainable practices such as biosecurity protocols, water quality practice biological control systems using probiotics and vaccines to be effective alternatives with lower reliance on antibiotics. These practices, if adopted across aquaculture systems, may increase farm productivity and fish health while playing a significant role in the global response to AMR.

This holistic strategy provides the means to combine aquaculture economic goals with social responsibility in public health and environmental sustainability. The research lays groundwork for future studies to enhance and diversify sustainable practices, allowing aquaculture to continue to grow as a robust and versatile food sector.

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