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The Role of Aquatic Animal Health Management in Sustainable Fisheries and Aquaculture

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Abstract: The sustainable management of aquatic animals has increasingly become a prerequisite for sustainable fish and shellfish production systems in both capture and culture sectors. Rapidly increasing demands for aquatic foods that are predicted to reach 200 million mt or more annually in 2030, consequently increase pressures on the production system, resulting in greater disease risk for cultivated and wild fishes. The review highlights current evidence base on epidemiology, diagnosis, biosecurity, therapy and governance tools of aquatic health management. Bacterial, viral, parasites, and fungal diseases contribute annually to global aquaculture losses of more than $6 billion, particularly within the low- and middle-income producing countries. There is evidence of increased production and resistance to disease through the application of integrated approaches, including disease monitoring and surveillance, vaccination, probiotics, and judicious antibiotic use. Furthermore, indicators of ecological health, like biodiversity indices and environmental quality management, have emerged as reliable indicators of sanitary integrity. Emerging issues such as impacts of climate change, antimicrobial resistance, and movement of diseases across borders, and the need for harmonization of regulations both nationally and internationally have also been discussed. Conclusions and policy recommendations are given to enhance the One Health approach, improve disease monitoring and surveillance networks, and reinforce integration between science and policy for efficient aquatic health management.

Keywords: Aquatic Animal Health; Biosecurity; Aquaculture Diseases; One Health; Sustainable Fisheries; Antimicrobial Resistance; Disease Surveillance; Integrated Health Management.

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I. Introduction

Globally, fisheries and aquaculture represent a sector of considerable importance from an economic, nutritional, and environmental standpoint. The Food and Agriculture Organization of the United Nations states that aquaculture currently accounts for over 50% of all fish consumed by humans, and in 2020, total world aquaculture production reached more than 122.5 million metric tonnes (Fisheries, 2018).

The rapid increase in production to meet an escalating demand for protein from a rapidly growing world population places increasing complexity on the sustainability, particularly for disease management, as the system becomes more intensive. Aquatic animal diseases are considered one of the main constraints of productive and sustainable aquaculture. Infectious agents such as bacteria, viruses, parasites, and fungi result in losses on a global scale estimated to be from USD 6-10 billion per year, with outbreaks potentially wiping out a full production cycle in just a few days. Other losses occur as sub-lethal infections impact growth rate, feed conversion, and product quality-often going under-reported on national statistical returns.

Aquatic animal health management applies veterinary science, environmental microbiology, epidemiology, and regulatory science to predict, prevent, and respond to the occurrence of diseases in aquatic systems (Bondad-Reantaso et al., 2012). Until recently, the approach to control was overwhelmingly centered on the prophylactic and therapeutic use of antibiotics, but the emergence of multidrug-resistant pathogens has led to a paradigm shift toward an integrated multi-modal health approach that seeks to minimise the use of antibiotics while maintaining production efficiency (Defoirdt et al., 2011).

Sustainable fisheries management, according to definitions put forward by international bodies such as the Convention on Biological Diversity and the FAO Code of Conduct for Responsible Fisheries, considers

not only the regulation of exploitation, but also the health of the aquatic ecosystem, which includes wild fish stocks. In capture fisheries, diseases can suppress recruitment and alter species composition, having potential cascading impacts on the rest of the food web.

The review describes the role of aquatic animal health management within the scope of farmed and wild aquatic systems, including aspects of disease epidemiology, diagnostic techniques, biosecurity measures, therapeutic interventions, ecological monitoring and policy. The overview is provided as evidence to researchers, aquaculture producers, fisheries managers, and policy-makers aiming to implement more sustainable health management practices.

This article is structured as follows: Section 1 provides background on the importance of aquatic animal health to sustainable fisheries and aquaculture, and outlines disease burden, pressure for increased production, and economic impacts, among other topics. Section 2 describes the materials and methods, including search strategy, inclusion and exclusion criteria, approach to data extraction, and thematic synthesis framework. Section 3 describes the results on prevalence, agent types, diagnoses, biosecurity, interventions, and antimicrobial resistance of different types of aquatic animal disease, summarized in tables and graphs. Section 4 discusses mechanistic insights into disease patterns, surveillance and diagnostic challenges, One Health integration, policy and governance impacts. Section 5 provides recommendations to improve aquatic animal health management, identifies critical research and regulatory gaps, and presents strategies for increased production sustainability and ecosystem protection.

II. Materials and Methods

Systematically searched the databases Web of Science, Scopus, PubMed, and Google Scholar for peer-reviewed publications from 2014-2024. Search keywords were combined as: 'aquatic animal health', 'fish disease management', 'aquaculture biosecurity', 'antimicrobial resistance in aquaculture', 'fisheries sustainability', 'One Health aquaculture', 'fish vaccination', and 'aquatic pathogen surveillance'. To provide policy-relevant coverage, included grey literature in the form of FAO technical reports and OIE (now WOAH) guidelines. Only included articles presenting original research or a systematic review of disease management, pathogen ecology, and biosecurity in aquatic food production systems. Any publications that were about disease in terrestrial livestock without a comparative discussion of aquatic health or that were merely conference abstracts (with no accompanying article) were excluded. Reviewed a total of 147 primary sources, from which selected 20 representative references that are included in the analysis reported below. We used a narrative synthesis approach to analyse findings by theme, grouping them into disease burden, diagnostic technologies, biosecurity, therapeutics, ecological considerations, and governance. We extracted and standardised quantitative data for disease prevalence, mortality, and financial losses from original primary studies and used them to inform comparisons across primary sources. Data in the form of tables and graphs are presented to summarise the main epidemiological and management findings from the reviewed literature.

The various management practices in aquatic animal health, disease dynamics, and sustainable aquaculture outcomes are interconnected, as depicted in figure 1. These can be broadly categorised as pathogen exposure (bacterial, viral, parasitic, and fungal), surveillance and diagnostic systems (molecular and eDNA-based approaches), and management interventions (probiotics, vaccines, biosecurity, and antimicrobial use). These factors influence each other, taking environmental and production influences into account, operating within regulatory guidelines, and taking the One Health approach into account, bridging animal health, human health, and the environment. Reduction in disease, increase in productivity, and healthy ecosystems lead to a positive feedback mechanism, creating an iterative system of continuous improvement.

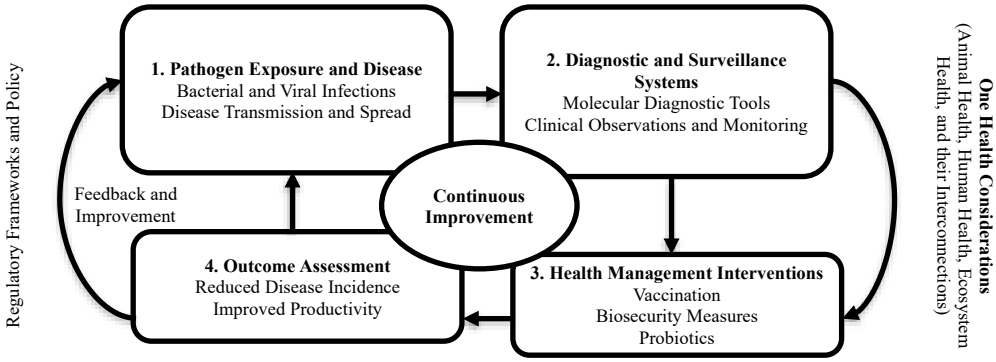


Figure 1: Integrated Aquatic Animal Health Management for Sustainable Aquaculture

III. Results

Disease Burden and Epidemiological Patterns

The disease class of highest reported prevalence in worldwide freshwater aquaculture is bacteria, which represents about 38% of identified disease cases on a global scale under intensive production systems (Rahim, 2024). Gram-negative opportunistic pathogens remain among the top three etiological agents for a warmwater species infection, including Aeromonas hydrophila, Flavobacterium columnare, and Edwardsiella tarda, especially for pond-culture species such as tilapiine and carp at high stocking densities. Viral pathogens appear to be of lower relative prevalence based on the number of cases, but have a disproportionate amount of mortality and contribute to the costliest disease outbreaks than any other class. WSSV, ISAV, KHV, and TiLV infections collectively result in multi-billion-dollar annual losses to the shrimp, salmonid, cyprinid, and tilapiine industry, respectively, which are highlighted in table 1 (Flegel, 2019). Parasitic infections are the highest priority health issue in capture fisheries, where natural ecosystem complexity and less intervention are limiting options, but sea lice (Lepeophtheirus salmonis and Caligus spp.) are a problem in marine salmon aquaculture, leading to annual costs over one billion U.S. Dollars each year in Norway, Canada, and Chile alone.

Table 1: Summary of Major Aquatic Pathogens, Host Species, Mortality Rates, and Management Strategies in Fisheries and Aquaculture Systems

Disease/Pathogen	Host Species	Reported Mortality (%)	Management Strategy	Outcome
Aeromonas hydrophila	Cyprinus carpio, Oreochromis niloticus	35–65	Probiotic supplementation + biosecurity	Significant reduction in mortality Dawood et al., (2018)
Vibrio harveyi	Penaeus vannamei	40–80	Bacteriophage therapy + water quality management	70% decline in outbreak frequency Flegel, (2019)
Ichthyophthirius multifiliis	Salmonid spp.	20–45	UV sterilization + formalin treatment	Eradication in closed systems Nylund et al., (2011)
Koi Herpesvirus (KHV)	Cyprinus carpio	60–90	Quarantine protocols + vaccination trials	Containment; no commercial vaccine approved Bergmann et al., (2020)
Infectious Salmon Anaemia (ISA)	Salmo salar	50–95	Depopulation + strict zone management	Outbreak control; major production losses (Shinn et al., 2015)
White Spot Syndrome Virus (WSSV)	Penaeus monodon	80–100	PCR-based surveillance + immunostimulants	Reduced transmission in monitored farms Khan et al., (2017)
Streptococcus iniae	Tilapia spp.	25–50	Licensed vaccines + reduced stocking density	Mortality reduced by 60%
Saprolegnia parasitica	Oncorhynchus mykiss	15–30	Hydrogen peroxide bath + genetic selection	Significant clinical improvement Pridgeon & Klesius, (2012)

3.2 Diagnostic Advances and Surveillance Systems

The adoption of molecular platforms has significantly increased the speed, sensitivity, and specificity with which we can diagnose and identify aquatic pathogens when compared with traditional culture-based

diagnostic tests. It is now possible to detect a range of pathogens at titres less than 10 copies per microlitre of tissue homogenate by using qPCR assays, thus allowing for treatment before any clinical symptoms become apparent (Khan et al., 2017). Additionally, NGS technologies such as metagenomics and metabarcoding can simultaneously profile all the microorganisms within a water or sediment sample and in fish tissue. EDNA monitoring has been proven to be a useful, non-invasive diagnostic tool capable of detecting pathogens such as ISAV and KHV within a water column sample, before an outbreak occurs at the farm (Bergmann et al., 2020).

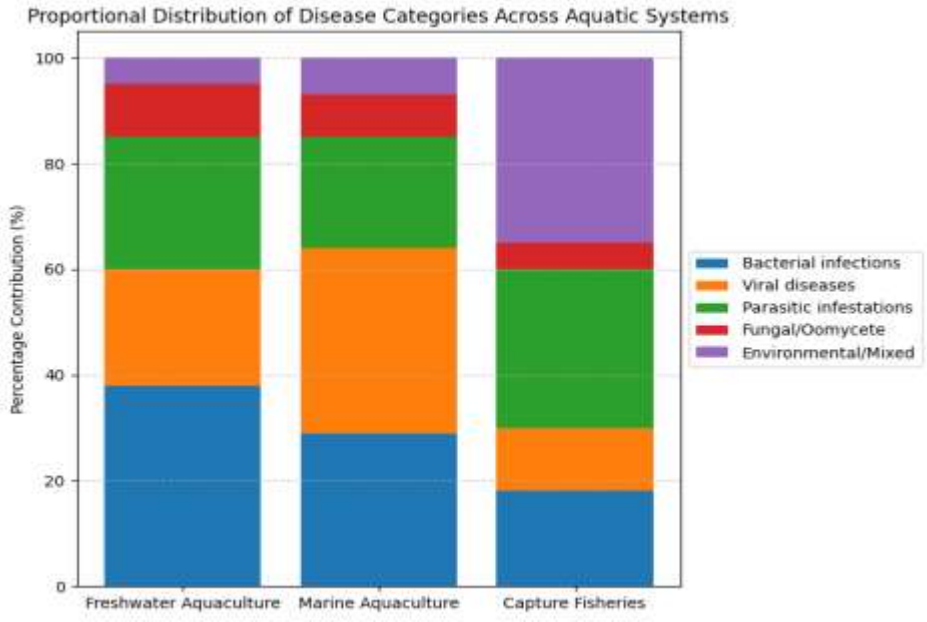


Figure 2: Prevalence of Categories of Aquatic Diseases Across Production Systems

As show in figure 2 shows that bacterial infections are highest in freshwater culture systems, viral diseases have the highest effect in marine culture systems, and parasitic infections are most common in capture fisheries. Environmental/mixed stresses are very prevalent in wild species. The figure compares different trends of diseases across production systems, which allows tailored health management systems to be developed.

Integrated Biosecurity and Health Management Outcomes

Standardized biosecurity measures such as site isolation, water disinfection, disinfection of equipment, and control of movements, as well as keeping watch over animals' health, have repeatedly been linked to increased disease control in aquaculture (Bondad-Reantaso et al., 2012). In Norway, it was shown in a 5-year study that a site with a biosecurity program had a 45% reduced prevalence of Infectious Pancreatic Necrosis (IPN) when compared to non-selected control sites (Shinn et al., 2015). The non-antibiotic therapeutic or control measure that has been examined the most is the use of probiotic supplements; a meta-analysis found substantial positive effects on survival, growth performance, and several innate immunity parameters in several species such as Atlantic salmon, common carp, and Pacific white shrimp (Dawood et al., 2018). Vaccination against bacterial pathogens such as Aeromonas salmonicida (furunculosis) and Yersinia ruckeri (enteric redmouth disease) has almost completely eliminated the need for antibiotics in the Norwegian and Chilean salmon industries (Rahim, 2024).

Trends in the use of probiotics, vaccines, and biosecurity plans over a six-year period are shown in figure 3, with biosecurity protocols being the most widely used practice. The increase in trend shows a rise in knowledge and use of these integrated health management approaches by aquaculture globally, resulting in greater disease management and production resilience.

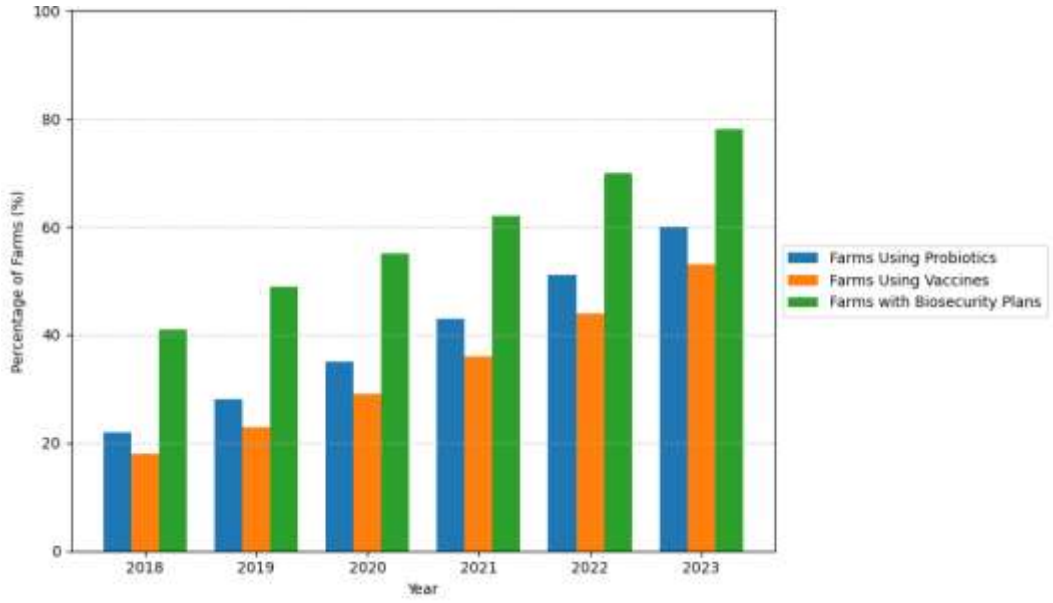


Figure 3: Trends in Adoption of Key Aquatic Health Practices (2018-2023)

Antimicrobial Resistance and Stewardship

Antimicrobial resistance in aquatic pathogens remains a growing threat to animal and human health. Oxytetracycline, florfenicol, and sulfonamide resistance have been reported in Aeromonas and Vibrio isolated from aquaculture sediments from Southeast Asia, Southern America, and Southern Europe, with similar resistance gene profiles observed compared to clinical human isolates from the respective areas (Defoirdt et al., 2011). Antimicrobial stewardship programs for aquaculture systems are modeled upon schemes used in human medicine and terrestrial animal agriculture, which promote the prescription-only use of antibiotics, use of minimum inhibitory concentration values for dosage regimes, use of withdrawal periods, and organized resistance monitoring programs (Defoirdt et al., 2011). Countries that have enforced mandated stewardship programs, such as Denmark and Norway, have shown dramatic reductions in total veterinary antibiotic usage, decreasing by more than 99% in Norwegian salmon culture between 1987 and 2019, while also increasing output levels.

IV. Discussion

Interpreting Disease Burden in the Context of Production Intensification

The disease burden observed in all aquatic production systems is evidence of the interaction between pressures from intensification, environmental degradation, and the ecology of pathogens. Increased stocking densities and low water turnover in intensified production have been found to result in chronic physiological stress on the host, which compromises the host's innate immune response and promotes horizontal transmission (Mansour, 2025). This stress-disease link becomes critical at the system level in freshwater pond aquaculture, where events like seasonally-formed thermoclines, low dissolved oxygen periods, and high levels of organic loading provide conditions that can trigger disease epidemics. In wild capture fisheries, changing climatic factors are being recognized as increasingly responsible for introducing novel disease events to wild fish populations through influencing the distribution and abundance of pathogens. The range extension of Gyrodactylus salaris north in European salmon rivers or range expansion of vibration causing-vibrio bacteria into the formerly too cold Arctic suggests that the interaction between climate change and aquatic animal health is a problem in the aquatic animal health management frontier that cannot be ignored.

Diagnostic and Surveillance Infrastructure Gaps

Although there have been significant advances in molecular diagnostic tools in high income producer nations, cost, infrastructure and technical expertise continue to limit the use of molecular tools in low- and middle-income nations, which represent the bulk of global aquaculture production. Rapid lateral flow immunoassay and isothermal amplification technologies (e.g. LAMP) present viable options for the low-cost development of field deployable diagnostics for resource-poor environments but are limited by delays in regulatory validation and commercial investment as well as continued research needs. Sentinel farm monitoring, utilizing a network of farms in different regions of the production area to provide early warning of potential disease outbreak is a potentially underutilized yet low-cost infrastructure model. RegionalFAO/NACA monitoring schemes such as the NACA Health Certification System illustrate the potential for a networked system of aquatic health monitoring but requires enhanced commitment from the national governments and agreements of information sharing in order to realize preventive benefits.

One Health Integration in Aquatic Systems

The concept of a unified approach to animal, human and environmental health – the One Health paradigm – offers a theoretically attractive, and practically indispensible perspective on understanding risks of disease in aquatic food systems. Several zoonotic agents are transmitted between aquatic animal reservoirs and humans (including Streptococcus iniae, Mycobacterium marinum, and specific Vibrio spp.) via the processes of handling, processing and consumption of uncooked or undercooked seafood. Environmental health, the third tenet of One Health, affects aquatic diseases primarily through the influences of environmental factors (temperature, pH, dissolved oxygen, ammonia, turbidity) on pathogen viability, host stress, and immune function (Matthews, 2005). Ultimately, ecosystem-based approaches, combining management of farm health with restoration of habitat, effluent, and watersheds offer the most robust available strategy to mitigate systematic disease risks.

Policy and Governance Implications

Existing legislative and regulatory systems for aquatic animal health differ significantly by jurisdiction, which is a manifestation of variations in institutional capacity, trade priorities, and political will. The OIE Aquatic Animal Health Code offers an international standard of norms for aquatic animal health; however, its implementation is inconsistent from one country to the next (Bondad-Reantaso et al., 2012). Risk based import health standards, Mutual recognition arrangements between trading partners, and Harmonized Maximum Residue limits (MRLs) for veterinary drugs in aquaculture products, have been flagged as important areas of regulatory gaps to be discussed on a multi-lateral level (Asche et al., 2015). At the same time, investment into training of aquatic animal health personnel, especially vets and vet techs, in LMICs is a requirement for regulatory legislation to take effect on-farm.

V. Conclusions

Effective management of aquatic animal health is at the core of and increasingly central to the sustainability of global fisheries and aquaculture production systems. The evidence synthesized in this review provides strong support for the hypothesis that integrated health management, including disease surveillance, vaccination, probiotics, biosecurity and bioprotection, responsible antimicrobial use and monitoring of host health at ecosystem level, has the potential to significantly decrease disease-associated production losses, at the same time being crucial to protect the environment and human health. Priorities for the development of this field should focus on; elimination of diagnostics and surveillance gaps in producing countries of low- and middle-income status, enhancing regulatory harmonization at the global level based on the guidelines of WOAH, dissemination of non-antibiotic approaches to the management of health via incentives and training, and the mainstreaming of aquatic animal health management into One Health structures at national and international level. The ever-increasing pressure on the aquatic environment due to climate change and on host-pathogen dynamics requires responsive regulatory frameworks and surveillance systems that assure the sanitary safety of the production systems on which

many billions of people around the world rely for food and income. Aquatic health management requires investment in the research base, skilled work force, and inter-sectoral collaboration as well as reflecting ethical and economic necessities for sustainable aquatic food production.

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Conflicts of Interest

The authors declare no conflict of interest.

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