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Review

Ensuring Fish Safety Through Sustainable Aquaculture Practices

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Abstract

Sustainable aquaculture is increasingly vital to meet global protein demands while ensuring fish product safety and environmental stewardship. This review addresses fish hygiene as a comprehensive, multi-stage challenge encompassing water quality management, pathogen control, responsible veterinary drug use, feeding practices, humane slaughter, post-harvest handling, and monitoring systems. We examined current practices and technologies that promote hygienic standards and reduce contamination risks across production cycles. The integration of biosecurity measures and alternative health-promoting agents contributes to disease prevention and reduces reliance on antimicrobials. Responsible drug administration aligned with regulatory frameworks minimizes residues and antimicrobial resistance. Feeding strategies incorporating sustainable and safe ingredients further support fish health and product quality. Critical control points during slaughter and post-harvest processing ensure microbial safety and prolong shelf life. Advanced monitoring and traceability systems enable real-time oversight and enhance food safety assurance. Finally, certification programs and robust regulatory policies are essential to standardize practices and facilitate access to international markets. Collectively, these strategies foster sustainable aquaculture that safeguards public health, maintains ecological integrity, and supports economic viability. This holistic approach positions fish hygiene not as a final quality check, but as an integral, continuously managed component of responsible aquaculture production.

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1. Introduction

Aquaculture has rapidly become the fastest-growing segment of animal food production worldwide, now supplying over half of all seafood consumed globally [1]. This expansion is largely driven by the urgent need to ensure global food security amid a growing population, increasing demand for protein, and stagnating wild fisheries [2,3]. Projections indicate that demand for aquatic food will increase substantially by 2050 [4,5]. This transformation aligns with the 2030 Agenda for Sustainable Development, which recognizes the role of aquaculture in promoting food and nutrition security, while encouraging the responsible use of natural resources and reducing poverty [6]. As the sector intensifies and diversifies to meet these expectations, the implementation of rigorous hygiene standards across the production cycle becomes a fundamental requirement, not only to safeguard consumer health but also to ensure long-term productivity, ecological balance, and public trust.

Fish hygiene refers to a set of practices and conditions that aim to minimize biological, chemical, and physical contamination in aquaculture products [7]. It encompasses various stages of the production chain, including water quality control, feed management, disease prevention, slaughtering, and post-harvest handling. Inadequate hygienic conditions can lead to the proliferation of pathogens, the presence of drug residues, and the deterioration of organoleptic and nutritional quality, ultimately compromising food safety and marketability.

The integration of hygiene protocols with sustainability principles enhances the resilience and credibility of aquaculture systems [8]. Sustainable aquaculture not only seeks economic viability and environmental stewardship but also prioritizes animal health, biosafety, and public health outcomes [9]. The adoption of good hygienic practices aligned with environmental and social responsibility contributes to reduced antimicrobial resistance, improved resource efficiency, and greater access to international markets that demand traceable and certified products [10].

This review explores the critical intersections between fish hygiene and sustainable aquaculture. By addressing key aspects such as water quality, prophylactic measures, responsible drug use, feeding strategies, slaughtering, monitoring systems, and regulatory frameworks, we aim to identify science-based strategies that promote safe, ethical, and competitive aquaculture practices in alignment with global public health goals.

2. Water Quality Management: A Pillar for Fish Hygiene and Sustainable Aquaculture

Water quality management is one of the fundamental pillars of sustainable practices in aquaculture, being crucial for fish health, the safety of the final product, and the efficiency of production systems [11,12]. Fish are essential components of aquatic ecosystems; they play key roles in the food chain and help maintain these environments in a delicate balance, providing a stress-free habitat for the fish [13]. Aquatic organisms are highly sensitive to environmental conditions, and even subtle variations in the physicochemical parameters of water can cause physiological alterations, increased stress, impaired immune responses, and greater susceptibility to diseases, directly impacting animal welfare and the sanitary quality of products destined for human consumption [14].

In aquaculture production systems, the deterioration of water quality, characterized by the accumulation of toxic compounds such as ammonia, nitrite, and hydrogen sulfide, low dissolved oxygen levels, harmful algal blooms, and proliferation of pathogenic bacteria, compromises zootechnical performance, promotes infections, and increases mortality rates. Recent studies have linked disease outbreaks, mass mortality events, and productivity declines to poor water quality, often exacerbated by environmental degradation and climate change, including floods, droughts, and ocean acidification, especially in coastal systems [15,16].

In this context, improving water quality, combined with maintaining stable environmental factors and proper water exchange management, emerges as an essential strategy to reduce disease incidence in aquaculture environments [17]. Integrated water quality management involves biological processes such as biofiltration and nitrification, which remove toxic compounds, as well as effluent treatment systems, including sedimentation tanks, constructed wetlands, and UV disinfection, that minimize environmental impact and enable safe water reuse.

Recirculating Aquaculture Systems (RAS) have stood out as central technology to optimize water use, promote sustainability, and ensure high hygiene standards by allowing continuous treatment and reuse of water within the system [18]. Complementarily, Integrated Multi-Trophic Aquaculture (IMTA) contributes to ecological balance and nutrient recycling by combining species at different trophic levels to improve water quality and system sustainability [19].

Innovations in routine monitoring and automation, utilizing intelligent sensors, the Internet of Things (IoT), and artificial intelligence (AI), enable rapid anomaly detection, remote control, and automated responses, increasing operational efficiency, reducing labor dependency, and fostering a more resilient future for aquaculture [20]. Sustainable aquaculture incorporates a variety of strategies to manage water quality effectively, including biological, physical, and technological approaches, which are detailed in the following sections.

2.1. Recirculating Aquaculture Systems (RAS)

Given the need to promote environmental sustainability and the increasing vulnerability of aquaculture to the effects of climate change, Recirculating Aquaculture Systems (RAS) have emerged as a promising adaptation strategy [18, 21bad]. These closed-loop systems represent a modern approach to intensive aquaculture production, combining high productivity with environmental responsibility. By enabling continuous water filtration and reuse, RAS significantly reduce water consumption and effluent discharge, thereby minimizing the environmental impact of the activity. Additionally, they allow for precise control of water physicochemical parameters, enhancing biosafety and the sanitary quality of the products [22].

Due to their technically closed and controlled configuration, RAS also pose minimal risk of negative ecological impacts, such as habitat degradation, pollution, and eutrophication of water bodies, biodiversity loss caused by the escape of farmed organisms or the introduction of exotic species, as well as the spread of diseases and parasites [21]. Another important advantage is their resilience to extreme climate events, including fluctuations in precipitation, droughts, floods, cyclones, salinity shifts, ocean acidification, and sea level rise, making them a stable alternative in scenarios of environmental instability [23]. Despite these advantages, two major factors still hinder their widespread adoption: high energy consumption and the associated emissions of greenhouse gases (GHG) [21,24]. Moreover, the technical complexity and high implementation costs limit their application, particularly in developing countries [25].

In this context, the development of technological innovations that enable more accessible, energy-efficient, and low-carbon RAS is urgently needed. Such advancements are essential to support a resilient aquaculture sector capable of meeting the growing global demand for safe and high-quality fish products, thereby contributing to the effective assurance of food security and fish safety in the face of 21st-century environmental challenges.

2.2. Biofiltration and Nitrification

One of the main challenges in intensive aquaculture systems is the accumulation of toxic nitrogenous compounds, especially ammonia (ionized NH_4^+ and non-ionic NH_3), originating from fish excretions, uneaten feed, and organic waste [26]. In RAS, efficient control of these compounds is essential to maintain optimal water conditions, safeguard fish health, and ensure the hygiene of the final product [27].

A central component of water treatment in these systems is the nitrifying biofilter, which houses microbial communities capable of converting ammonia into nitrate (NO_3^-) through a two-step nitrification process: ammonia is first oxidized to nitrite (NO_2^-) by ammonia-oxidizing bacteria (AOB), and subsequently to nitrate by nitrite-oxidizing bacteria (NOB) [28]. This conversion is crucial to avoid toxic water chemistry, reduce physiological stress, and prevent immune suppression or disease outbreaks.

To establish a functional nitrifying community, these bacteria typically form biofilms that adhere to high-surface-area substrates within the biofilter [29]. The formation, stability, and activity of these biofilms are regulated by quorum sensing mechanisms, which coordinate gene expression for biofilm development and nitrification [30]. A well-established biofilm ensures consistent removal of nitrogenous waste, contributing directly to biosafety and the microbiological quality of aquaculture products.

Beyond classical nitrification, advanced molecular studies have revealed the presence of other microbial players in RAS biofilters, such as anaerobic ammonium-oxidizing (anammox) bacteria, complete ammonia oxidizers (comammox), and heterotrophic denitrifiers, which support nitrogen removal through alternative pathways [31]. These consortia enhance system resilience and reduce dependence on water exchange, aligning with the principles of sustainable and resource-efficient aquaculture [26].

Optimizing biofilter performance, including the choice of substrates, microbial colonization protocols, and startup strategies, is critical for improving system stability and minimizing environmental impact. Innovative approaches, such as the use of quorum sensing stimulants to accelerate biofilm formation, show promising potential but require further validation [30]. As biofiltration technologies continue to evolve, they offer increasing potential to strengthen water quality control, enhance fish welfare, and ensure the hygienic and sustainable production of aquaculture products.

2.3. Effluent Treatment and Water Reuse

The management of aquaculture effluents is a key element in ensuring both environmental sustainability and fish hygiene [32]. Historically, the discharge of untreated wastewater has been associated with the spread of diseases across watersheds, prompting the global implementation of wastewater treatment technologies [33]. In aquaculture, where large volumes of water are used and discharged, effluent treatment is essential to reduce environmental impact, prevent the dissemination of pathogens, and enable the safe reuse of water within closed systems [34].

Modern effluent treatment systems in aquaculture draw inspiration from natural biochemical, physical, and microbiological processes [35]. These technologies can be categorized into intensive ("hard") systems, such as activated sludge and membrane bioreactors, which require high energy input and compact infrastructure, and extensive ("soft") systems, such as constructed wetlands and infiltration-percolation units, which depend on larger surface areas and longer hydraulic retention times [34]. While intensive approaches are suitable for high-density or urban operations, extensive systems offer low-energy, low-maintenance alternatives for small-scale or rural aquaculture, enhancing accessibility and ecological integration [36].

Effluent treatment in reuse-oriented systems typically involves multiple stages: mechanical solid separation, biological treatment for organic matter with nitrogen removal, and disinfection to eliminate pathogenic microorganisms [32]. The final quality of the treated water depends on the treatment sequence employed and operational conditions. Advanced processes such as ultrafiltration, reverse osmosis, and membrane bioreactors (MBR) have significantly improved the removal of suspended solids, nutrients, and microbial contaminants, enabling safe reuse within the production cycle or for secondary purposes such as irrigation [34].

Responsible effluent management, through sedimentation tanks, constructed wetlands, or UV disinfection, reduces the environmental footprint of aquaculture operations while minimizing the risk of introducing external contaminants [37,38]. Among these, UV disinfection stands out for its ability to inactivate a wide range of pathogens without producing chemical residues, making it particularly suitable for applications where microbial water quality is critical [39,40]. In closed-loop systems, such RAS, UV treatment is often applied as a final polishing step, helping maintain high hygienic standards in recirculated water and supporting biosecurity protocols aimed at disease prevention [35].

The reuse of treated water is increasingly recognized not only as a sustainability strategy but also as a response to growing water scarcity, particularly in arid and semi-arid regions. In some watersheds, treated effluent already constitutes a significant portion of streamflow. Concepts such as Managed Aquifer Recharge (MAR) and potable reuse are emerging as innovative tools within integrated water resource management [41]. In aquaculture, water reuse reduces dependence on natural sources, minimizes discharge, and contributes to maintaining stable water parameters, crucial for fish health and for minimizing disease outbreaks [42]. Recent developments also reflect a paradigm shift in wastewater treatment: from energy-intensive processes to potentially energy-neutral or even energy-generating facilities. By incorporating decision-support systems, risk-based management, and circular economy principles, wastewater treatment is becoming a strategic component of sustainable aquaculture planning [35].

Effluent treatment and water reuse are thus not only environmental imperatives but also critical pillars for ensuring fish hygiene and public health. By closing the water loop and maintaining strict control over microbial and chemical parameters, aquaculture operations can enhance biosecurity, reduce contamination risks, and contribute to the global transition toward sustainable food systems.

2.4. Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable farming approach that involves the co-cultivation of species from different trophic levels within the same system [43]. Typically, fed species such as finfish are combined with extractive organisms like bivalves (e.g., mussels, oysters), deposit feeders (e.g., sea cucumbers), and macroalgae (e.g., kelp), which assimilate organic and inorganic wastes generated by the fed species [44]. This nutrient recycling mechanism contributes to the reduction of environmental impacts, enhances overall system efficiency, and improves water quality, thereby supporting hygienic conditions and the health of farmed organisms [45].

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IMTA systems address one of the core challenges in aquaculture: nutrient enrich-ment and organic loading from uneaten feed and metabolic waste [46]. By integrating species that naturally absorb or filter these excess nutrients, IMTA not only reduces the ecological footprint of aquaculture operations but also transforms potential pollutants into valuable co-products [47]. This bioremediation function plays a crucial role in minimizing eutrophication risks and maintaining water clarity, both of which are funda-mental for fish welfare and disease prevention [48].

Initially developed in coastal and land-based systems, IMTA has gained increasing attention as a model for future offshore aquaculture. The shift from nearshore to open-ocean farming is driven by the need to reduce user conflicts and mitigate environmental degradation in coastal areas, while expanding the spatial capacity for sustainable seafood production [49]. Offshore IMTA represents a promising step toward large-scale, environmentally responsible marine aquaculture. However, it also presents unique technological and biological challenges, such as the development of resilient infrastructure capable of withstanding strong hydrodynamic forces while ensuring the effective growth and retention of extractive species [50].

Despite these challenges, ongoing research indicates that integrating extractive species offshore can enhance nutrient capture and contribute to greater ecosystem ser-vices, including carbon sequestration and habitat provisioning [44]. Moreover, IMTA systems can provide socioeconomic benefits to coastal communities, offering diversified income streams and opportunities for localized value chains through the cultivation of high-value species [51].

From a food safety perspective, IMTA also contributes to hygienic aquaculture by maintaining stable water parameters and reducing the concentration of potentially harmful waste byproducts. Improved water quality directly correlates with lower microbial loads, reduced disease incidence, and decreased reliance on antimicrobials, all of which align with global efforts to enhance fish safety and sustainable aquaculture practices [52].

As the aquaculture industry evolves to meet growing global demand for safe and sustainable seafood, IMTA emerges as a model capable of aligning productivity with environmental stewardship [46]. The development and optimization of IMTA systems, both nearshore and offshore, represent a critical step toward integrated, resilient, and ecologically sound aquaculture systems.

2.5. Routine Monitoring and Automation

Routine monitoring and automation play a transformative role in modern aquaculture by enabling real-time assessment of water parameters, ensuring rapid detection of anomalies, and allowing immediate corrective actions [53]. These technological advances not only safeguard fish welfare and hygiene, but also support sustainability and operational resilience.

Aquaculture faces numerous challenges, including environmental fluctuations, disease outbreaks, high labor dependency, and growing competition for clean water resources [54]. In this context, sensing and automation technologies emerge as powerful tools to overcome these constraints. Intelligent sensors integrated with Internet of Things (IoT) platforms, artificial intelligence (AI), and automated response systems enable continuous and remote monitoring of key parameters such as temperature, dissolved oxygen, pH, turbidity, and nutrient concentrations [55-57]. These systems provide timely and precise data that support early decision-making, reducing the risks of water quality deterioration and associated health impacts on cultured species.

Beyond water quality, these technologies enhance disease surveillance through biosensors and image-based diagnostics, enabling early detection and mitigation of outbreaks [58]. They also contribute to environmental monitoring, especially in managing feeding practices, a key factor in water pollution. Automated feeding systems, informed by real-time behavioral and environmental data, minimize feed waste, reduce organic load, and help maintain optimal water conditions [59].

Moreover, automation reduces the reliance on manual labor for routine tasks such as sampling, animal behavior observation, and parameter measurement [57]. This alleviates labor intensity while increasing consistency, accuracy, and productivity. Underwater cameras, machine vision systems, and motion capture technologies are increasingly used to monitor animal welfare, feeding activity, and system integrity with minimal human interference [58].

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Wireless sensor networks (WSNs), cloud platforms, and mobile interfaces further facilitate the integration of aquaculture operations, enabling stakeholders to visualize and manage systems in real time from any location [60]. When combined with big data analytics and AI, these technologies allow predictive modeling and automated decision-making, fostering adaptive and resilient farm management [61].

Adoption of sensing and automation technologies is not merely a trend, but a foundational shift toward smarter, safer, and more sustainable aquaculture. These innovations enhance hygiene standards, optimize resource use, mitigate environmental impacts, and contribute decisively to securing aquatic food systems in the face of global challenges.

3. Pathogen Control and Disease Prevention

Effective pathogen control and disease prevention are essential pillars of fish hygiene and are intrinsically linked to the success of sustainable aquaculture systems [62]. Disease outbreaks remain among the most significant challenges in fish farming, often resulting in substantial economic losses, compromised animal welfare, and reduced product quality [63. Proactive and integrated health management strategies are critical to minimizing microbial contamination and ensuring the safety of fish for human consumption.

Aquatic environments naturally harbor a wide range of microorganisms, including opportunistic pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., *Flavobacterium columnare*, and parasites like *Ichthyophthirius multifiliis* [64, 65]. In intensive production systems, poor water quality, high stocking densities, and inadequate biosecurity measures can exacerbate the proliferation of these pathogens and increase disease susceptibility [66]

Pathogens, including bacteria, viruses, fungi, and parasites, pose constant threats to cultured species, especially in environments under chronic stress. Effective control relies on a multi-layered strategy that includes environmental management, biosecurity protocols, routine health monitoring, and prophylactic measures [67,68]. For example, water quality management through filtration, disinfection, and biofiltration helps reduce pathogen loads and physiological stress, thereby supporting immune function.

Biosecurity protocols such as quarantine of new stock, equipment disinfection, restricted access to facilities, and regular sanitation routines are essential to prevent the introduction and spread of infectious agents [69]. Complementarily, vaccination programs and the use of immunostimulants have been successfully applied in various aquaculture species to enhance resistance against specific pathogens [70].

Early disease detection plays a crucial role in reducing mortality and production losses. Routine monitoring using clinical observation, histopathology, molecular diagnostics (e.g., PCR), and emerging biosensor technologies allows for rapid diagnosis and targeted interventions [71]. These approaches are particularly relevant in reducing antibiotic reliance, mitigating antimicrobial resistance, and promoting sustainable health practices.

Overall, pathogen control and disease prevention form the cornerstone of fish hygiene in aquaculture, ensuring animal welfare, minimizing production losses, and safeguarding public health by reducing the risk of contaminated or unsafe seafood reaching consumers.

3.1. Biosecurity Protocols

Biosecurity protocols are essential to minimize the risk of pathogen introduction and spread in aquaculture systems, thereby protecting fish health, productivity, and product safety [69,72]. Defined as a set of scientific measures designed to exclude pathogens from cultured environments and hosts, biosecurity involves comprehensive management practices including control of stock quality, water treatment, facility hygiene, and proper handling of personnel, equipment, and waste [73].

Major transmission routes for pathogens include introduced animals such as broodstock and fry, humans, vehicles, equipment, water sources, feed, and organic waste. To mitigate these risks, quarantine procedures and the use of Wireless sensor networks) stocks are critical to ensure healthy introductions [74]. Additionally, strict access controls, personnel hygiene training, disinfection protocols, and sanitation measures help prevent cross-contamination via people and equipment [75].

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Water treatment strategies, such as filtration, disinfection, and the use of recirculating aquaculture systems, reduce pathogen load in the culture environment [39]. Proper feed handling is equally important to minimize microbial contamination and pathogen transmission [76,77]. Moreover, effective waste management helps to prevent the proliferation of pathogens within production systems and their release into natural ecosystems [78]. Segregation of production stages is another important measure to limit internal contamination. Continuous surveillance combined with detailed record-keeping enhances the effectiveness of biosecurity plans and facilitates rapid response to emerging threats [79].

Recent technological advances, including real-time environmental sensor networks, big data analytics, machine learning, remote sensing, and geographic information systems (GIS)—have significantly improved disease risk monitoring and management at both farm and regional levels [80].

Looking ahead, future biosecurity strategies will likely emphasize integrated, risk-based approaches that combine preventive measures, technological innovations, and robust regulatory frameworks [81]. These efforts are critical to ensuring animal health, environmental sustainability, and the long-term viability of aquaculture operations in an increasingly complex and disease-prone global context.

3.2. Prophylactic Measures

Prophylactic measures, particularly vaccination, are essential tools in modern aquaculture to prevent infectious diseases and reduce the dependence on antibiotics [82]. Aquaculture currently accounts for approximately 41% of the global fish supply, and as production intensifies, the sector has faced increased outbreaks caused by a range of pathogens including bacteria, viruses, fungi, and ectoparasites [1]. Historically, antibiotics and chemical treatments have been employed to control such diseases; however, their indiscriminate use has led to the emergence of antimicrobial resistance (AMR) in aquatic environments, affecting not only fish health but also posing significant threats to food safety and public health [83].

One of the main consequences of antibiotic residues and resistant bacteria in sediments and water columns is primarily attributed to therapeutic applications in aquaculture [84,85]. This has raised global concern regarding the horizontal transfer of resistance genes among aquatic and terrestrial microbes, increasing the likelihood of multidrug-resistant pathogens entering the food chain [86]. In response, the development and implementation of vaccines have gained traction as a sustainable and preventive alternative [87]. Unlike antibiotics, vaccines do not leave residues, do not promote resistance, and can offer long-lasting immunity against specific pathogens [88].

Several vaccine types have been developed using advanced biotechnological methods, such as inactivated, live-attenuated, subunit, recombinant protein, and DNA-based vaccines [89]. While traditional vaccines remain widely used, next-generation platforms offer improved safety profiles, targeted delivery, and stronger immunogenicity, especially when combined with adjuvants and novel delivery systems like nanoparticles [89,62]. However, challenges remain regarding administration routes, particularly in small or juvenile fish (inter-species variability in immune responses), and ensuring long-term protection in dynamic aquatic environments [90].

Commercially available vaccines remain limited for several economically important aquaculture species, especially those with complex immune responses or diverse farming conditions [91]. In addition, regulatory, financial, and technical challenges continue to hinder the widespread adoption of promising experimental vaccines in practical field applications [90]. Nevertheless, advances in molecular biology and biotechnology, such as next-generation sequencing and immunoproteomics, have greatly enhanced the characterization of fish-pathogen interactions and identification of virulence factors, facilitating the rational design of safer and more effective vaccines [92,93]

Despite these challenges, vaccination programs have successfully reduced disease outbreaks in many aquaculture regions. For example, the introduction of vaccines targeting *Aeromonas salmonicida* and *Vibrio anguillarum* in salmonids has led to significant decreases in antibiotic use in Norway, demonstrating the critical role of vaccination in disease control [94,87]. These successes highlight the need for continued research on vaccine efficacy across diverse species and varying environmental conditions, considering the complexity of pathogen dynamics within aquaculture ecosystems.

To meet future demands, sustained investment and collaborative efforts among researchers, industry stakeholders, and policymakers are essential. Emphasis should be placed on developing polyvalent vaccines that protect against multiple pathogens, as well as innovative delivery systems tailored for mass immunization, including oral and immersion vaccines suitable for small or juvenile fish [90,95]. As vaccine-based prophylaxis evolves, it remains a cornerstone strategy for reducing antibiotic reliance, improving fish welfare, and ensuring the sustainability and safety of aquaculture production.

3.3. Alternative Health-Promoting Agents

The growing concern over antimicrobial resistance and environmental impacts of conventional chemotherapeutics has intensified the search for safer and more sustainable alternatives in aquaculture health management. Among the most promising approaches are phytotherapeutics derived from medicinal plants, which offer antimicrobial, antiparasitic, antiviral, antioxidant, and immunomodulatory effects without the risks associated with antibiotic residues or resistance [96,97].

These bioactive compounds, such as flavonoids, alkaloids, terpenoids, polysaccharides, and essential oils, can be administered in various forms (powder, crude extracts, or isolated compounds) and have demonstrated efficacy in enhancing disease resistance and promoting fish welfare [98]. Their natural origin, biodegradability, and broad-spectrum biological activities make them suitable for both intensive and small-scale aquaculture systems. Furthermore, the versatility of phytotherapeutics allows for integration with other strategies such as feed supplementation and immunostimulation, thus contributing to holistic and eco-friendly health management [99].

In addition to phytotherapeutics, probiotics and prebiotics have gained traction as effective health-promoting agents. Probiotics, defined as live microorganisms that confer health benefits when administered in adequate amounts, have been shown to enhance gut microbiota balance, modulate immune responses, improve nutrient digestibility, and increase resistance to pathogens [100,101]. Prebiotics, such as fructooligosaccharides (FOS) and mannanoligosaccharides (MOS), act as selective substrates for beneficial bacteria and further support innate immunity in fish [102,103].

Their combination, known as symbiotics, offers synergistic effects and has shown particular promise in key aquaculture species such as tilapia and salmon. Moreover, emerging biotechnological tools, including bacteriophages, antimicrobial peptides, biosurfactants, and algal extracts, are being explored for their unique mechanisms of action and low environmental impact [104]. Collectively, these alternative agents represent critical tools for reducing antibiotic dependence, improving fish health and resilience, and advancing sustainable aquaculture practices in line with global food safety and environmental goals.

3.4. Environmental Management

Sustainable aquaculture relies heavily on effective environmental management to minimize pathogen presence and control disease incidence [105]. Maintaining the health of aquatic animals requires the proactive control of water quality, sediment dynamics, and waste accumulation [106]. Regular tank cleaning, the optimization of feeding practices to prevent organic overload, and mitigation of environmental stressors such as low dissolved oxygen and temperature fluctuations are proven strategies to reduce the risk of opportunistic infections and parasite proliferation in aquaculture systems [107]

Beyond these operational practices, environmental management in aquaculture must be understood as a systematic approach that includes the identification of potential ecological impacts, the formulation of environmental standards, the implementation of Best Management Practices (BMPs), and continuous monitoring to ensure compliance [108]. When deviations are detected, such as excessive turbidity in effluents or nutrient loads beyond regulatory thresholds, corrective measures must be enacted to restore balance and protect both cultured species and surrounding ecosystems [105]. This process is particularly critical in intensive systems, where nutrient-rich effluents can lead to eutrophication, harmful algal blooms, and subsequent fish mortality.

Climate change exacerbates these environmental vulnerabilities. Increasing water scarcity, altered rainfall patterns, and rising temperatures directly affect aquaculture productivity and indirectly increase susceptibility to diseases [109,110]. These stressors compromise water quality and favor the proliferation of pathogens such as *Vibrio spp*. in shrimp farming or sea lice (*Lepeophtheirus salmonis*) in salmon culture, which have already caused significant economic losses [111,112]. As such, climate-resilient aquaculture systems must integrate adaptive environmental management practices, including the use of RAS, constructed wetlands for effluent polishing, and spatial planning to avoid habitat degradation and biodiversity loss.

Furthermore, the intensification of aquaculture has led to substantial pressures on freshwater resources and land use [113]. Predictions indicate that water consumption for aquaculture may more than double by 2050, accompanied by increasing demand for terrestrial feed ingredients [22]. Improper site selection and conversion of sensitive habitats, such as mangroves and rice field, to aquaculture facilities have already led to severe ecological consequences, including the depletion of wild brood stocks and irreversible biodiversity loss [114]. Addressing these concerns requires strong regulatory frameworks, the establishment of ecosystem-based management principles, and international cooperation to ensure compliance, especially in regions where environmental governance is weak or underfunded.

Integrated environmental management is not only a tool for disease prevention and fish hygiene, but also a critical strategy for ensuring the long-term sustainability and social license of the aquaculture industry. It must be supported by government policies, private-sector accountability, and transdisciplinary research capable of guiding adaptive responses to evolving climatic and ecological challenges.

3.5. Early Detection and Surveillance

In aquaculture systems, fish health assessments typically begin with visual inspections based on behavioral and morphological indicators. However, environmental conditions, such as water turbidity, sediment type, turbulence, and variable climatic factors, can obscure visibility, limiting the early detection of clinical signs and complicating health monitoring compared to terrestrial animals [115,116]. These challenges underscore the importance of early pathogen detection as a cornerstone of effective health management. To reduce morbidity and mortality rates, diagnostic approaches must balance sensitivity, specificity, speed, and cost-effectiveness [117]. Routine health surveillance through bacteriological, parasitological, and histopathological analyses remains a practical strategy under field conditions, but its effectiveness is constrained by the diversity of farmed species and the dynamic nature of aquatic environments [118,119].

Advancements in molecular diagnostics have significantly improved the sensitivity, specificity, and speed of pathogen identification. Techniques such as polymerase chain reaction (PCR), quantitative PCR (qPCR), and loop-mediated isothermal amplification (LAMP) have become widely adopted in fish health management [120]. More recently, environmental DNA (eDNA) detection and next-generation sequencing (NGS) have emerged as powerful tools capable of identifying pathogens without requiring direct sampling from infected fish. These approaches enable non-invasive, high-throughput diagnostics, which are particularly valuable in early-stage infections and large-scale operations [117,121,122].

Despite progress, several challenges remain. Diagnosis in aquaculture is often reactive rather than preventive, and routine surveillance is frequently underfunded, especially in low- and middle-income regions. Budget constraints and logistical barriers limit sampling frequency and coverage, and in many areas, monitoring is only carried out during disease outbreaks [117]. Moreover, emerging diseases with unknown etiologies, such as swollen skin disease or red spot syndrome, underscore the need for robust surveillance systems capable of detecting novel pathogens [119].

Future advances in early disease detection will focus on two main technologies: artificial intelligence (AI) and environmental DNA (eDNA). AI-based tools can accelerate visual diagnostics and increase efficiency but require extensive training datasets. eDNA offers a sensitive and versatile method for detecting pathogens both in the field and in the lab, especially when sampling is optimized. These technologies, along with tools like remote sensing and telemedicine, hold great

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promise for improving disease prevention in aquaculture. However, their adoption still faces challenges related to infrastructure and technical capacity, particularly in small-scale or resource-limited settings [117,57, 123].

The development of tailored diagnostic strategies for specific species and production systems is also essential. With over 600 aquatic species farmed globally, a one-size-fits-all approach is not feasible [124]. Environmental conditions, species behavior, and production intensity all influence disease dynamics and diagnostic feasibility [120]. Therefore, surveillance protocols must be adapted to the biological and operational realities of each system.

A comprehensive surveillance framework, combining conventional, molecular, and emerging digital technologies, is key to reducing mortality, minimizing antimicrobial use, and ensuring fish hygiene. As aquaculture intensifies and climate-related stressors increase disease susceptibility, strengthening early detection capabilities is not only a matter of animal health, but also a critical component of food safety, environmental sustainability, and economic resilience in the sector.

4. Responsible Use of Veterinary Drugs

The growing relevance of aquaculture within global food systems has underscored the importance of veterinary drugs in ensuring fish health and productivity. Antibiotics, antifungals, antiparasitics, and disinfectants remain essential tools for controlling disease outbreaks, particularly in intensive farming systems with high stocking densities and elevated risks of pathogen transmission [125]. However, the indiscriminate or prophylactic use of these compounds has raised critical concerns regarding antimicrobial resistance (AMR), environmental contamination, and food safety [87,126].

Numerous studies have reported the frequent use of veterinary drugs without professional prescription, improper dosage administration, and low recovery rates in farmed fish, particularly in low-resource settings [127]. In several regions, a significant proportion of treatments are carried out without veterinary oversight, with farmers often relying on empirical practices rather than science-based protocols. This misuse results in subtherapeutic exposure, the emergence of resistant bacterial strains, and the persistence of drug residues in aquatic environments and fish tissues [128, 129].

AMR in aquaculture poses a global One Health challenge. Resistant bacteria and resistance genes can spread horizontally across microbial communities in aquatic ecosystems and vertically along the food chain, potentially reaching human consumers and wild populations [130]. Residues of common antibiotics such as sulfamethazine, oxytetracycline and tetracycline have been detected in surface waters, sediments, and edible fish tissues, sometimes exceeding regulatory thresholds [131]. This persistence not only threatens aquatic biodiversity but may also compromise the marketability of fish products, particularly in export-driven economies.

Beyond antibiotics, other veterinary agents, such as formalin, malachite green, and chloramine-T, have also raised toxicological concerns. While effective against parasites and microbial contaminants, many of these compounds are associated with carcinogenic or mutagenic risks [132,133], and their continued use without rigorous oversight can lead to ecological imbalance and long-term environmental degradation.

To mitigate these risks, sustainable aquaculture practices emphasize the responsible and judicious use of veterinary drugs within a broader health management framework. Biosecurity protocols, such as pathogen exclusion, water quality control, density optimization, and the sourcing of disease-free fry, are crucial preventive strategies that reduce drug reliance [69]. In addition, IMTA systems, which combine species from different trophic levels, offer ecosystem-based solutions to waste recycling and disease mitigation [44,45].

Complementary to these practices, the adoption of alternatives such as probiotics, prebiotics, immunostimulants, and vaccines has gained momentum. These agents enhance innate immunity, modulate gut microbiota, and reduce disease susceptibility without contributing to AMR or chemical pollution [102]. Notably, vaccination programs have substantially reduced antibiotic usage in salmon farming, serving as a model for other species and production systems.

Safeguarding fish hygiene through the responsible use of veterinary drugs requires a multifaceted approach involving regulatory enforcement, farmer education, surveillance systems,

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and investment in sustainable health-promoting alternatives. As aquaculture continues to expand under climate and resource pressures, aligning therapeutic practices with One Health and food safety principles is not only necessary for public and environmental health, but also essential for the long-term viability and credibility of the sector.

4.1. Minimizing Antimicrobial Resistance (AMR)

The widespread use of antibiotics in aquaculture has emerged as a significant concern due to its contribution to the development and dissemination of AMR in aquatic and terrestrial environments [87]. As aquaculture intensifies to meet global seafood demand, the reliance on antibiotic, particularly in countries with limited regulatory oversight, has led to the selection of resistant bacteria and the accumulation of antibiotic residues in farmed fish, sediments, and surrounding waters [128]. Studies have shown that up to 80% of antibiotics administered via medicated feed are excreted unmetabolized, contaminating the environment and exerting selective pressure even at sub-inhibitory concentrations [86, 88,134,135].

Open aquaculture systems are particularly vulnerable to environmental dissemination of AMR genes due to direct exchange with coastal waters and sediments, where horizontal gene transfer (HGT) between microbial communities is facilitated. Genes such as tet, bla, sul, and qnr have been widely detected in marine sediments adjacent to fish farms, often linked to mobile genetic elements like plasmids and integrons, which further increase their spread across bacterial taxa [136-138]. Such resistomes pose a direct risk to public health, especially as zoonotic pathogens found in aquaculture systems (e.g., *Aeromonas hydrophila*, *Vibrio vulnificus*, *Mycobacterium marinum*) may harbor clinically relevant AMR genes [139,140].

Closed systems, such as RAS, offer a promising approach to minimize AMR dissemination by reducing environmental discharge and enabling better control of water quality and waste treatment [22,102,141,142]. However, even in RAS, biofilms in filters and tank surfaces can act as reservoirs of resistance genes, particularly when antibiotics are used therapeutically or prophylactically [143,144]. Therefore, while RAS reduce the external environmental impact, they do not eliminate internal AMR selection pressures.

Mitigation strategies to combat AMR in aquaculture must be multifaceted. Key approaches include strict regulation of antibiotic use, routine residue monitoring, and adoption of alternative health management tools such as vaccines, probiotics, phage therapy, and quorum sensing inhibitors [66]. Regulatory successes, like the prohibition of prophylactic antibiotic use in Europe (Directive 2001/82/EC) and the drastic reduction in antibiotic use in Norwegian salmon farming via vaccination and best practices, illustrate the effectiveness of integrated management strategies [145].

Moreover, water disinfection methods (e.g., UV and ozone) and improved sludge treatment protocols further reduce environmental loading of antimicrobials [146,147]. Equally important is the need for international harmonization of AMR surveillance and reporting in aquaculture, particularly in low- and middle-income countries where 90% of global production occurs [148]. Investment in research to elucidate AMR transfer pathways and the resilience of resistance genes in aquaculture environments is essential for developing evidence-based interventions.

Minimizing AMR in aquaculture requires a One Health approach that considers the interconnectedness of aquatic environments, farmed species, human health, and global trade. Ensuring fish hygiene and food safety in sustainable aquaculture must include proactive AMR control to prevent future public health crises and preserve the efficacy of life-saving antibiotics.

4.2. Compliance with Withdrawal Periods

Ensuring strict compliance with withdrawal periods is essential to prevent the presence of veterinary drug residues, especially antimicrobials, in aquaculture products, particularly fish fillets intended for human consumption. Antimicrobials can accumulate in fish tissues before being fully metabolized or excreted, making the occurrence of residues more likely when animals are harvested during treatment or before the end of the regulatory withdrawal period [149,150]. These withdrawal periods refer to the minimum time interval between the last administration of a veterinary drug and the harvesting of the animal, allowing residue levels to decrease below the established Maximum

Residue Limits (MRLs) set by national and international regulatory bodies, including the Codex Alimentarius, the European Medicines Agency (EMA), and the World Organisation for Animal Health (WOAH) [151,152].

Consumption of products containing antimicrobial residues can pose various risks to human health, including allergic reactions, toxicity, and, most importantly, the development and dissemination of antimicrobial resistance along the food chain [152,153]. Furthermore, improper use of these drugs, such as administration outside the recommended dose or period, contributes to residue presence in tissues [154]. The use of prohibited substances such as chloramphenicol, nitrofurazone, nitroimidazoles, and fluoroquinolones is particularly concerning and must be strictly controlled [155].

To protect public health, international organizations define MRLs, which are the maximum safe limits for the presence of drugs and their metabolites in animal tissues. Although global harmonization efforts have been promoted mainly by the World Trade Organization (WTO) and Codex Alimentarius, MRLs still vary between countries, reflecting differences in regulations and local veterinary drug use practices. Many developing countries still lack their own regulations, complicating uniformity in international food safety [152,156]. For example, the European Union establishes specific MRL values for cultured fish, contributing to rigorous control of these residues [157].

Failure to comply with withdrawal periods can result in detectable residues in edible tissues, posing risks to consumer health and leading to trade restrictions or product rejections in international markets. Beyond health impacts, this situation undermines consumer confidence and the credibility of the aquaculture industry. Therefore, many countries have implemented monitoring programs and residue surveillance systems to ensure compliance and traceability throughout the production chain [77].

From the perspective of sustainable aquaculture, adherence to withdrawal periods should be supported by detailed record-keeping, responsible veterinary supervision, and producer training. Technologies such as automated feeding systems, digital tracking tools, and barcode batch identification are increasingly employed to optimize treatment management and prevent premature harvesting. Harmonized international guidelines also assist in standardizing safety limits, facilitating fair trade and global consumer protection. Thus, by rigorously complying with withdrawal periods and respecting established MRLs, aquaculture systems enhance food safety, reduce the risk of antimicrobial resistance selection, and maintain access to demanding international markets. Integrating these practices within comprehensive fish hygiene management strategies reinforces the commitment to safe, sustainable, and responsible aquaculture.

4.3. Monitoring and Record Keeping

The implementation of robust pharmacovigilance systems alongside effective traceability protocols is fundamental to overseeing the use of veterinary drugs in aquaculture [158]. Maintaining accurate and detailed records of all administered treatments enables producers and regulatory authorities to assess compliance with established guidelines, swiftly identify any irregularities, and implement timely corrective actions [159]. Such transparency throughout the production cycle is essential for ensuring fish health, food safety, and consumer confidence.

Furthermore, comprehensive monitoring allows for the early detection of adverse drug reactions or treatment failures, providing critical feedback to veterinarians and producers for optimizing therapeutic strategies [160]. Digital record-keeping systems facilitate data integration and real-time reporting, enhancing regulatory oversight and supporting research on drug efficacy and resistance patterns. In addition, traceability from hatchery to harvest promotes accountability, enabling rapid response to food safety incidents and bolstering market access both domestically and internationally [161]. Ultimately, effective monitoring and record-keeping underpin sustainable aquaculture practices by fostering responsible drug use, minimizing the risk of antimicrobial resistance development, and protecting ecosystem health.

4.4. Environmental Considerations

Veterinary drugs administered in aquaculture are not always fully metabolized by fish and can persist in the aquatic environment, accumulating in sediments and potentially impacting non-target organisms [162]. This bioaccumulation poses risks to the ecological balance by affecting microbial communities, benthic invertebrates, and other aquatic species, which may lead to disruptions in nutrient cycling and ecosystem functioning [163].

To promote sustainability, aquaculture operations should implement comprehensive effluent treatment strategies aimed at reducing the release of pharmaceutical residues into surrounding waters [40]. Sediment management practices, such as regular removal or stabilization of contaminated deposits, can further mitigate environmental contamination [164]. Additionally, the development and use of eco-friendly drug formulations with enhanced biodegradability and reduced toxicity can substantially minimize adverse effects on the aquatic environment [165].

Integrating these environmental considerations within veterinary drug use protocols supports the protection of biodiversity and helps preserve the health of aquatic ecosystems, ensuring that aquaculture remains a viable and responsible food production system for the future.

5. Feeding Practices and Product Safety: A Critical Link in Fish Hygiene and Sustainable Aquaculture

In modern aquaculture, feeding practices play a pivotal role in determining the health, welfare, and overall productivity of farmed fish. As the global demand for aquatic products rises, the need for nutritionally balanced, cost-effective, and environmentally sustainable diets has become increasingly urgent. Fish, like other vertebrates, rely on precise combinations of macronutrients and micronutrients to sustain essential physiological processes such as growth, immune function, reproduction, and adaptation to stress [166].

Feed formulation is not merely a technical endeavor, it is a critical pillar of sustainable aquaculture. The selection of ingredients and the nutritional design of feeds directly affect feed conversion efficiency, environmental footprint, product quality, and economic viability [167,168]. Hence, the use of species-specific, bioavailable, and functionally effective feed components is central to responsible fish farming [169,170].

This section examines the core principles of nutritional formulation and fish physiology, with particular attention to nutrient requirements, digestion and absorption, the role of protein, lipids, carbohydrates, vitamins, and minerals, as well as the evaluation of alternative and functional feed ingredients [171,166]. Understanding these elements is key to improving feeding strategies, reducing ecological impacts, and ensuring the safety and quality of aquaculture products throughout the production chain [168].

5.1. Nutritional Formulation and Fish Physiology

Fish nutritional needs vary according to their digestive physiology, feeding habits, and developmental stage. A species-specific approach to nutrient formulation and absorption mechanisms is essential for efficient and sustainable aquaculture practices [172].

Proteins are the primary structural and functional components of fish tissues, essential for maintenance, growth, and reproduction. They supply indispensable amino acids such as lysine, methionine, and threonine, which cannot be synthesized by the animal and must be provided through the diet. Protein requirements vary according to species and developmental stage, being typically higher for carnivorous fish and larval stages. Animal-based ingredients (e.g., fish meal, meat meal) and plant-based ingredients (e.g., soybean meal, pea meal) are used to formulate balanced amino acid profiles. However, plant sources often lack specific amino acids, such as methionine in soy or lysine in corn, requiring strategic combinations of ingredients to ensure nutritional adequacy [173].

Lipids serve both as a concentrated source of energy and as suppliers of essential fatty acids, such as linoleic acid (omega-6) and linolenic acid (omega-3), along with highly unsaturated fatty acids like EPA and DHA, which are particularly critical for marine fish [174]. These fatty acids are vital for membrane integrity, immunity, reproduction, and growth. The inclusion of animal oils (e.g., cod liver oil) and vegetable oils (e.g., soybean, corn, coconut) in adequate proportions is necessary to fulfill the specific requirements of each species and enhance the final product quality, particularly regarding omega-3 content with benefits for human health [175,176].

Carbohydrates, though not essential, function as cost-effective energy sources and contribute to feed pellet stability. Carnivorous species have limited ability to metabolize carbohydrates, while omnivorous and herbivorous fish like tilapia utilize them more efficiently. Carbohydrate inclusion levels typically range from 25% to 55% depending on species and developmental stage [173,177,178].

Vitamins and minerals, though required in small quantities, are indispensable for immune competence, metabolic regulation, bone formation, and reproductive performance. Vitamins C and E, for example, act as antioxidants and have been linked to enhanced disease resistance when used at levels above the minimum requirement [179,180]. Minerals such as phosphorus, calcium, magnesium, and trace elements must be supplied in bioavailable forms, especially in confined farming systems where natural food is limited [181,182].

With growing environmental concerns and limitations in the use of fishmeal and fish oil, the search for alternative ingredients has intensified. Plant proteins, insects, microbial biomass, and agro-industrial by-products are being evaluated based on digestibility, nutrient composition, absence of anti-nutritional factors, and impact on performance [183]. Functional feed additives, such as β-glucans, nucleotides, and pigments, are also incorporated to improve immune responses, stress tolerance, and feed efficiency [184,185].

Effective feed formulation must also consider palatability, water stability, and feeding behavior. Understanding whether a species is a surface, column, or bottom feeder allows for the development of feed formats that reduce waste and improve nutrient retention [186]. Feed composition influences not only the health and growth of the animals but also the environmental impact through nutrient excretion, particularly phosphorus. The use of phytase enzymes, for example, has been shown to increase phosphorus availability and reduce water pollution [187].

5.2. Feed Ingredients and Contaminant Control

The careful selection and quality control of feed ingredients are fundamental steps to ensure not only the productive performance of aquaculture species but also the safety of the final product for human consumption. Ingredient evaluation involves essential aspects such as digestibility, palatability, and nutrient utilization efficiency. These factors are influenced by experimental strategies that consider diet planning, feeding regimes, feces collection methods, and the parameters used for data analysis [168].

Ingredient digestibility determines the fraction of nutrients effectively absorbed by the animals, while palatability directly impacts feed intake [188]. Nutrient utilization refers to the fish's metabolic capacity to convert dietary inputs into growth and physiological maintenance. Evaluating these variables, both individually and in an integrated manner, is essential for formulating balanced and effective diets that promote animal health and reduce waste.

Among the main contaminants reported in aquafeed ingredients are mycotoxins, heavy metals (such as mercury, lead, and cadmium), residues of veterinary drugs, agricultural chemicals, persistent organic pollutants, industrial solvents, melamine, and pathogens like *Salmonella* [189-193]. The presence of these contaminants poses risks not only to farmed fish health but also to human consumers, due to the potential for bioaccumulation and transfer through the food chain.

To mitigate these risks, robust quality control systems must be implemented at all stages of feed production, from supplier selection to ingredient storage. Variability in raw materials, especially in regionally sourced or minimally processed ingredients like rice bran or animal by-products, requires continuous monitoring through physical, chemical, and biological analyses. The use of rapid screening tests and in-house laboratories in feed mills is recommended to detect adulteration and ensure batch compliance [194].

The Food and Agriculture Organization (FAO) and the Codex Alimentarius Commission play a key role in setting international guidelines for food safety and quality standards [195]. The growing public concern about antibiotic residues and chemical contaminants in farmed seafood highlights the urgent need to adopt sustainable and transparent practices throughout the aquafeed production chain [87].

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Therefore, traceability, standardization, and continuous updates to safety protocols are key elements to ensure that feed is not only nutritionally effective but also safe and aligned with the principles of sustainable aquaculture.

5.3. Alternative Protein Sources and Sustainability

Aquaculture has the potential to play a key role in global food security over the coming decades. However, it still faces significant environmental challenges, particularly regarding the sustainability of feed inputs. Conventional protein sources, such as fishmeal and fish oil derived from wild-caught forage fish, are increasingly unsustainable due to overfishing and stagnant production levels [196].

A variety of alternative protein sources have been explored to replace fishmeal in aquafeeds, each offering distinct advantages and limitations. Among these, insect meal stands out for its high nutritional value, efficient feed conversion, and low environmental footprint. Insects can be reared on organic waste streams, requiring minimal land and water use [197]. Additionally, sustainable sources such as macro- and microalgae, microbial biomass (e.g., yeasts and single-cell proteins), fishery by-products, and a variety of plant-derived ingredients (e.g., soybean, corn gluten, and rapeseed meals) have shown promise [198-200]. These alternatives vary in terms of amino acid profiles, digestibility, scalability, and market acceptance, and may be used individually or in combination depending on species-specific dietary needs and local resource availability.

Although plant-based proteins and animal by-products like meat and bone meal and poultry meal have been widely utilized as fishmeal replacements, these ingredients present critical limitations. Antinutritional factors, low digestibility in carnivorous species, and the environmental impact of large-scale agriculture raise concerns about their long-term viability [201]. Genetic engineering and bioprocessing have been employed to improve the nutritional quality of plant ingredients, reduce antinutritional compounds, and adapt their profiles to the needs of aquaculture species [202,203]. Nevertheless, complete replacement of fish-based ingredients remains a challenge for many carnivorous fish, such as salmon and tuna, due to their specific dietary requirements [204].

To complement the limitations of conventional and alternative ingredients, the development of functional feed additives, many derived from microbial biomass, has emerged as a promising strategy to improve feed efficiency, health, and growth performance. These additives can enhance immune function, reduce oxidative stress, and compensate for nutritional deficiencies in plant-based diets [205]. However, the mechanisms of action are often proprietary, and their effectiveness may vary among species.

Selective breeding programs also offer significant opportunities to improve the efficiency of fish in utilizing alternative protein sources [206]. Genetic variability in feed conversion efficiency and the ability to digest plant-based diets have been demonstrated in several aquaculture species, including rainbow trout, Nile tilapia, and black tiger shrimp [207-209]. Advances in genomic selection techniques further allow for accurate prediction of breeding values, enabling the development of strains better adapted to plant-based or insect-based feeds.

Freshwater omnivorous species such as tilapia, catfish, and herbivorous carps already require lower levels of fishmeal compared to marine carnivores. Shifting consumer preferences toward these species, supported by sustainability labeling and public education, could help reduce overall reliance on forage fish [210]. Moreover, integrating polyculture or multi-trophic aquaculture systems can increase protein yield per unit of input while providing ecological benefits such as nutrient bioremediation [205].

No single ingredient is likely to replace fishmeal entirely. Instead, a blend of multiple protein sources tailored to species-specific requirements can offer balanced nutrition and economic flexibility. Functional ingredients and dietary supplements may further enhance the efficacy of such blended diets. To ensure a socially and environmentally sustainable future for the aquaculture industry, it is essential to continue investing in the development and optimization of alternative protein sources, improve feed formulation technologies, and enhance animal performance through genetic, nutritional, and ecosystem-based innovations.

5.4. Functional Feeds and Health Promotion

Functional feeds represent an evolving concept in aquaculture nutrition, aiming not only to meet the basic nutritional requirements of aquatic species but also to enhance growth performance, feed utilization, stress resistance, and disease resilience. These feeds incorporate a broad range of dietary additives designed to deliver targeted physiological and immunological benefits, beyond standard nutritional supplementation [211].

Functional feed additives can be classified based on their primary functions. Acidifiers and exogenous enzymes, for example, improve digestibility and counteract anti-nutritional factors. Other additives, such as probiotics, prebiotics, phytogenics, and bioactive immunostimulants, are employed to modulate gut microbiota, boost immune function, and improve overall health. Bioactive immunostimulants, derived from natural sources such as plants, animals, microbes, algae, and yeasts, are among the most promising tools to enhance immune competence and disease resistance in aquaculture, providing an eco-friendly and non-toxic alternative to chemotherapeutics [185].

Numerous bioactive compounds, including fructooligosaccharides (FOS), butyric and propionic acids, chitosan, soy isoflavones, lentinan, lipoteichoic acid, lactoferrin, and fucoidan, have shown efficacy in improving growth, immunity, survival, and resistance to pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., *Streptococcus* spp., and various viral agents [212-214]. Their dietary application supports the development of robust fish health, especially in the context of reducing disease outbreaks and improving aquaculture productivity sustainably.

These compounds act through several mechanisms, including enhancing antioxidant and anti-inflammatory properties, stimulating innate immune responses (e.g., phagocytic activity, lysozyme action, oxidative burst), and modulating cytokine expression [215,216]. Furthermore, immunostimulants influence intestinal health by promoting beneficial microbiota, reducing oxidative stress markers such as malondialdehyde (MDA), and regulating immune signaling pathways (e.g., MyD88, TNF-α, TGF-β) [217]. Their role in maintaining mucosal immunity and improving digestive enzyme activity has been well documented, particularly in species such as rainbow trout (*Oncorhynchus mykiss*) and koi carp (*Cyprinus carpio*) [214,218].

Among these, plant-derived bioactive compounds (e.g., flavonoids, alkaloids, terpenoids, saponins, and essential oils) have attracted considerable interest due to their growth-promoting, antimicrobial, appetite-stimulating, and anti-stress effects. These phytogenics are not only effective but also safe for fish, consumers, and the environment, offering a sustainable approach to health management in aquaculture. They stimulate digestive enzymes, modulate gut flora, enhance protein synthesis, and improve feed conversion rates without adverse effects [211].

Despite the benefits, some immunostimulants may cause immunosuppression if used in excess, and their long-term effects remain underexplored [219]. Nevertheless, functional feeds fortified with natural immunostimulants are considered a promising approach to improve fish resilience and reduce reliance on antibiotics and synthetic chemicals. Advances in diet formulation, coupled with precise dosing strategies and integration into selective breeding programs, can help optimize the use of these compounds for species-specific health and performance outcomes.

6. Slaughtering and Post-Harvest Handling: Critical Stages for Ensuring Fish Hygiene

Slaughtering and post-harvest handling represent crucial phases in the aquaculture value chain, with direct implications for fish hygiene, product quality, and food safety [10]. These stages are particularly sensitive to microbial contamination, tissue degradation, and oxidative spoilage, all of which can be exacerbated by substandard handling practices, and the presence of human pathogens and the formation of hista-mine caused by spoilage bacteria make the control of both pathogenic and spoilage microorganisms critical for fish product safety [220]. Therefore, integrating hygienic and sustainable protocols during harvest and post-harvest is essential for delivering safe aquaculture products to consumers [221,222].

6.1. Pre-Slaughter Management and Stress Reduction

Minimizing stress before slaughter not only supports animal welfare but also pre-serves meat quality by preventing the rapid exhaustion of energy stores, excessive lac-tic acid production, a decline in muscle pH, and premature rigor mortis [223,224]. Ac-cording to Vijayan et al. [225], tilapia (*Oreochromis mossambicus*) subjected to 2 hours of confinement stress showed increased glucose and lactate levels, reflecting heightened carbohydrate metabolism. Longer exposure to stress (24 hours) or elevated cortisol levels stimulated hepatic enzyme activity and raised free amino acid levels, indicative of intensified protein breakdown. As described by Poli et al. [223], two types of meta-bolic responses may occur in fish muscle post-mortem due to stress or cortisol expo-sure. Short-term, intense stress just before slaughter results in lactic acid production and lowered pH from enhanced anaerobic glycolysis. In contrast, prolonged or re-peated stress leads to energy depletion of lactic acid, resulting in a consistently high muscle pH due to insufficient glycolytic substrates.

Best practices in pre-slaughter management include fasting periods to reduce gut content [226], gentle handling [223,227], low stocking density during transport [228], and the use of anesthetics or sedation [229], all of which contribute to a more humane and hygienic slaughter process.

6.2. Hygienic Slaughtering Techniques

The method and environment of slaughter directly influence microbial contamination levels. Slaughtering must be conducted under clean and controlled conditions, using sanitized tools and surfaces to avoid cross-contamination [230]. Exsanguination should follow humane stunning techniques (e.g., percussive, electrical, or immersion in anesthetics) to reduce suffering and preserve fillet quality [231]. Live chilling, which entails the rapid reduction of body temperature in fish, is commonly employed as a pre-slaughter procedure, particularly for tropical species [232]. However, for cold-water species, this method is not recognized as humane, as it fails to induce immediate loss of consciousness and may cause prolonged distress prior to death [233]. Electrical stunning has emerged as one of the most effective and humane stunning methods, as it can induce immediate unconsciousness by delivering a sufficient electric current through the brain. This process triggers generalized epileptiform seizures, analogous to tonic-clonic seizures observed in mammals [234]. Physical destruction of the brain is another approach capable of inducing instantaneous unconsciousness and death. Among the physical methods, spiking (penetrating the brain with a sharp instrument such as a knife or awl) can be effective when accurately performed [235]. Nonetheless, due to the anatomical variability and small brain size of many fish species, the risk of unsuccessful application and subsequent animal suffering is significant. Consequently, spiking is seldom used in commercial aquaculture operations [236,237]. In contrast, percussive stunning (administering a calibrated mechanical blow to the cranium) is more frequently adopted. When properly executed, this technique causes immediate and irreversible unconsciousness via severe cerebral trauma, and is considered a viable method for maintaining animal welfare at slaughter [238].

On the other hand, maintaining strict sanitary conditions during fish processing is essential to ensure food safety and product quality [239]. This includes the use of clean, potable water for rinsing and processing, mandatory use of gloves to prevent cross-contamination, and prompt evisceration to reduce microbial proliferation in the visceral cavity. Additionally, the proper collection, handling, and disposal of processing waste are critical to avoid environmental contamination and limit the spread of pathogens throughout the production facility [240].

6.3. Storage and Cold Chain Integrity

The prompt application of ice or entry into refrigerated storage is essential to preserving sensory and microbiological quality of fish [221]. For these authors, freezing is commonly used to reduce microbial and enzymatic degradation, it is energy demanding and insufficient for long-term preservation due to its inability to fully prevent oxidative spoilage, and the addition of preservative additives (EDTA/TBHQ/ascorbic acid) could be the best possible way to preserve the fish and fish products. In sustainable systems, energy-efficient refrigeration technologies [241], use of solar-powered coolers [242,243], and eco-friendly packaging materials [244] can reduce environmental impact while maintaining hygiene standards.

To enhance product innovation, shelf life, and sustainability, the fish industry is investing in advanced processing (e.g., high hydrostatic pressure, osmotic dehydration, high-intensity pulsed light) and packaging (e.g., modified atmosphere, active, and intelligent systems) technologies. These efforts include the development of new approaches and the integration of existing ones to optimize product quality and reduce food loss [245].

6.4. Packaging

Appropriate packaging extends shelf life and prevents microbial ingress [246]. Vacuum packaging constitutes a passive form of hypobaric preservation extensively utilized in the food sector owing to its cost-effectiveness and capacity to limit oxidative deterioration and suppress the growth of aerobic spoilage microorganisms [247,248]. The process involves enclosing the product in a low-oxygen-permeable material and hermetically sealing it following air evacuation [248]. Modified atmosphere packaging (MAP) is effective in prolonging the shelf life of fishery products by suppressing microbial proliferation and oxidative processes. The extent of *shelf life* extension is influenced by multiple factors, including the fish species, lipid content, initial microbial load, composition of the gas mixture, the gas-to-product volume ratio, and most critically, the storage temperature [247]. The use of biodegradable and antimicrobial packaging materials aligns with sustainable practices while maintaining food safety. Labeling with traceability information further enhances transparency and compliance with international food safety standards [249].

7. Monitoring Systems and Food Safety Assurance in Sustainable Aquaculture

Effective monitoring systems are critical to ensuring food safety and maintaining hygiene standards throughout the aquaculture production chain, and involves delivering food that is nutritionally adequate, safe, sustainable, resilient, and ethically compliant [3]. In the context of sustainable aquaculture, these systems not only support the detection and control of hazards but also enhance transparency, traceability, and compliance with international safety regulations [250]. The integration of continuous monitoring strategies contributes directly to the production of hygienic and safe fish products while aligning with environmental and ethical sustainability goals [3,251].

7.1. Implementation of Hazard Analysis and Critical Control Points (HACCP)

The HACCP approach is a widely recognized framework for identifying, evaluating, and controlling hazards that may compromise food safety [252,253]. In aquaculture, HACCP are implemented to mitigate risks at identified critical control points (CCPs), including aquatic environment control, feed integrity, medication protocols, harvest procedures, and storage environments [254]. Each CCP in sustainable aquaculture is associated with specific limits, monitoring protocols, and corrective measures. This structured approach enables the proactive management of biological, chemical, and physical hazards, ensuring not only food safety but also environmental responsibility, animal welfare, and long-term viability of production systems [253,255].

7.2. Real-Time Environmental Monitoring

Modern aquaculture operations increasingly employ real-time monitoring technologies to track key environmental parameters that influence fish health and hygiene [81,256]. In aquaculture, tools like smart feeders, water quality monitors, biomass estimators, and underwater cameras have advanced from being manually operated to fully automated and intelligent. These technologies improve how easily, quickly, and accurately daily tasks are performed [257]. Sensors integrated into water systems can continuously measure temperature, dissolved oxygen, ammonia, pH, and turbidity [258]. These parameters are critical in preventing microbial growth, minimizing stress-induced immunosuppression in fish, and reducing the incidence of opportunistic infections [259]. Remote monitoring through IoT (Internet of Things) platforms allows for predictive decision-making and rapid response to deviations, integrating to Machine Learning (ML) models, and the Quantum Approximate Optimization Algorithm (QAOA) to enhance water quality monitoring and prediction in aquaculture [260].

7.3. Microbiological Testing and Contaminant Screening

Routine microbiological assessments of aquatic environments, infrastructure surfaces, and fish products plays a critical role in maintaining sanitary standards within sustainable aquaculture operations [261, 81]. By systematically identifying microbial hazards, these assessments support Hazard Analysis and Critical Control Points (HACCP) implementation and facilitate proactive risk management across the production chain [220, 261]. Quantification of total bacterial counts, presence of pathogens such as Aeromonas, Listeria, or Salmonella, and tests for antimicrobial residues ensure that the product meets national and international safety thresholds [220]. Contaminant screening in aquaculture and the fish industry extends beyond microbial hazards to include the detection of chemical contaminants such as heavy metals (e.g., mercury, cadmium, lead), pesticide residues, and biotoxins (e.g., microcystins, domoic acid) [255, 262-265]. These substances can accumulate in aquatic organisms due to environmental pollution or the use of contaminated feeds [266]. Regular screening is essential not only for compliance with food safety regulations but also to safeguard consumer health. Therefore, comprehensive monitoring programs are critical to identify and mitigate these risks before products reach the market.

7.4. Traceability and Blockchain Technologies

Traceability enables the tracking of food and feed from origin to consumer [267], and plays a critical role in managing ecological and social challenges in the fish industry. It ensures product quality and transparency at the production level, while informing consumers and supporting regulatory compliance across the supply chain [268]. In the aquaculture and fishery industries, the integration of digital technologies such as DNA barcoding, Radio Frequency Identification (RFID) tags, and blockchain systems is revolutionizing traceability and data integrity [253,269]. These tools are increasingly utilized to generate immutable, verifiable records across the production chain, including critical stages such as feed origin, veterinary treatments, water quality interventions, and harvest dates [270].

Barcoding, particularly DNA barcoding, enables precise species identification, reducing cases of mislabeling and fraud [271,272]. RFID tags provide real-time tracking of individual fish or batches, allowing for seamless monitoring of movement, storage conditions, and handling throughout the supply chain [273]. Meanwhile, blockchain technology offers a decentralized and tamper-proof ledger, ensuring that once data are recorded, such as treatment history or production inputs, they cannot be altered retroactively [274]. This enhances transparency and trust among producers, regulators, retailers, and consumers [253,269]. Collectively, these technologies support food safety, biosecurity, and sustainability objectives by improving the accountability and responsiveness of the aquaculture supply chain [253,269,270]. Moreover, their application aligns with increasing global demand for ethically sourced, high-quality aquatic products and compliance with stringent international trade regulations [270].

8. Regulatory Framework and Certification: Ensuring Fish Hygiene

A robust regulatory framework and the implementation of certification systems are essential pillars for guaranteeing fish hygiene and aligning aquaculture practices with sustainability standards [275]. These instruments establish the minimum requirements for water quality, animal welfare, drug usage, environmental impact, and food safety, while promoting traceability and market access for responsibly farmed aquatic products [276].

8.1. National and International Regulatory Standards

Regulatory frameworks vary globally but are often guided by international benchmarks established by organizations such as the Codex Alimentarius Commission, the World Health Organization (WHO), and the World Organisation for Animal Health (WOAH). These standards are crucial for harmonizing food safety criteria, especially for countries engaged in fish export [277].

At the national level, agencies like Brazil's MAPA (Ministério da Agricultura e Pecuária), the U.S. Food and Drug Administration (FDA), and the European Food Safety Authority (EFSA) define specific sanitary and environmental requirements. These include maximum residue limits (MRLs)

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for veterinary drugs, water quality parameters, and pathogen control in processing plants, directly impacting the hygienic quality of the final product [77].

8.2. Veterinary Drug Regulations and Compliance

A fundamental component of regulatory compliance in aquaculture is the approval, monitoring, and post-market surveillance of veterinary drugs (including antibiotics, antiparasitics, anesthetics, and vaccines) used for disease control and animal welfare [162]. This regulatory process ensures that only authorized substances, with proven safety, efficacy, and environmental compatibility, are employed in aquatic food production systems [278]. Approval typically involves rigorous scientific evaluation of the drug's pharmacokinetics, residue depletion, withdrawal periods, environmental fate, and toxicological impact on non-target organisms and human health [152]. Regulatory agencies, such as the European Medicines Agency (EMA), FDA, or Brazil's MAPA require compliance with MRLs to prevent harmful residues in fish products intended for human consumption.

Post-approval surveillance programs are essential for: Detecting off-label or unapproved use [279]; Monitoring the emergence of antimicrobial resistance (AMR) [280], Ensuring adherence to Good Aquaculture Practices (GAPs) [281]. Furthermore, compliance with international standards is critical for maintaining export eligibility and consumer trust. Therefore, effective regulatory oversight not only protects public health and aquatic ecosystems, but also enhances the sustainability and credibility of the global aquaculture industry.

8.3. Certification Programs for Sustainable and Hygienic Production

Third-party certification schemes have emerged as critical governance mechanisms in aquaculture, aiming to ensure that production systems meet rigorous sanitary, environmental, and ethical standards [282]. These programs serve as independent validators, bridging the gap between producers, regulators, and increasingly conscious consumers concerned with food safety, ecological impact, and animal welfare [283]. Programs like Aquaculture Stewardship Council (ASC), GlobalG.A.P. Aquaculture, Best Aquaculture Practices (BAP), Organic Standards (EU Organic, USDA Organic) assess farms against strict criteria related to: Biosecurity and hygiene (disease control, responsible drug use); Environmental impact (effluent management, habitat protection); Animal welfare (humane handling and slaughter); Feed sustainability (traceable, low-impact ingredients); Food safety and traceability (HACCP, contaminant monitoring). These certifications provide external verification that producers are meeting or exceeding national and international standards, thus facilitating the access to premium markets [284]. Moreover, third-party certification plays a crucial role in aligning aquaculture practices with the United Nations Sustainable Development Goals (SDGs), particularly those related to food security, environmental conservation, and sustainable consumption [285].

8.4. Periodic Audits and Training

Both public regulatory bodies and certifiers conduct routine and unannounced audits to assess compliance with hygiene and sustainability standards [286]. These audits evaluate facility sanitation, handling procedures, water quality logs, cold chain management, and worker hygiene practices [287]. Additionally, training programs for producers and workers are required to maintain standards, promote a culture of food safety, and ensure continuous improvement.

9. Conclusions

Fish hygiene is a critical determinant of public health, consumer confidence, and the overall success of aquaculture systems. In the context of sustainable aquaculture, hygiene must be addressed holistically, beginning with water quality management and extending through biosecurity, responsible drug use, sustainable feeding, humane slaughter, post-harvest handling, and continuous monitoring systems. Each stage of the production cycle plays a pivotal role in mitigating contamination risks and ensuring the microbiological and chemical safety of fish products.

Integrating sustainability principles into hygiene protocols not only enhances the quality and shelf life of aquaculture products but also reduces the sector's ecological footprint and fosters social responsibility. Best practices, such as minimizing antibiotic dependence, employing alternative feed sources, and maintaining strict traceability, align fish production with growing regulatory requirements and global market demands.

Moreover, certification programs and regulatory frameworks serve as essential tools to standardize practices, validate compliance, and open access to international markets. As aquaculture continues to expand to meet global protein needs, investment in research, technology adoption, and policy development will be fundamental to strengthen hygienic standards without compromising environmental or economic sustainability.

Ultimately, a sustainable aquaculture sector is one in which fish hygiene is not treated as a final quality check, but as an integral, continuously managed component of responsible production, ensuring food safety, protecting public health, and preserving ecosystem integrity.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AMR	Antimicrobial Resistance
AOB	Ammonia-Oxidizing Bacteria
ASC	Aquaculture Stewardship Council
BAP	Best Aquaculture Practices
BMPs	Best Management Practices
DHA	Docosahexaenoic Acid
DNA	Deoxyribonucleic Acid
EFSA	European Food Safety Authority
EMA	European Medicines Agency
EPA	Eicosapentaenoic Acid
FAO	Food And Agriculture Organization
FDA	Food And Drug Administration
FOS	Fructoolig Saccharides
GAP	Good Aquaculture Practices
GHG	Greenhouse Gases
GIS	Geographic Information Systems
HACCP	Hazard Analysis and Critical Control Points
HGT	Horizontal Gene Transfer
IMTA	Integrated Multi-Trophic Aquaculture
IoT	Internet Of Things
LAMP	Loop-Mediated Isothermal Amplification
MDA	Malondialdehyde
MAP	Modified Atmosphere Packaging
MAPA	Ministério Da Agricultura E Pecuária
MAR	Managed Aquifer Recharge
MBR	Membrane Bioreactor
MOS	Mannanoligosaccharides

MRL	Maximum Residue Limits
NGS	Next-Generation Sequencing
NOB	Nitrite-Oxidizing Bacteria
PCR	Polymerase Chain Reaction
QAOA	Quantum Approximate Optimization Algorithm
RAS	Recirculating Aquaculture Systems
RFID	Radio Frequency Identification
SDGs	Sustainable Development Goals
SPF	Specific Pathogen Free
TGF	Transforming Growth Factor
TNF	Tumor Necrosis Factor
UV	Ultraviolet
WHO	World Health Organization
WOAH	World Organisation for Animal Health
WSNs	Wireless Sensor Networks
WTO	World Trade Organization

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