

Ensuring Fish Safety Through Sustainable Aquaculture Practices

Camila Carlino-Costa ¹  and Marco Antonio de Andrade Belo ^{2,*}

¹ Department of One Health, Sao Paulo State University (UNESP), Jaboticabal 14884-900, SP, Brazil; camila.carlino@unesp.br

² Laboratory of Animal Pharmacology and Toxicology, Brazil University, Descalvado 13690-000, SP, Brazil

* Correspondence: marco.belo@ub.edu.br

Abstract

Sustainable aquaculture is increasingly vital to meet global protein demands while ensuring fish product safety and environmental stewardship from a One Health perspective. This review addresses fish hygiene as a comprehensive, multi-stage challenge encompassing water quality management, pathogen control, antimicrobial stewardship, 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.



Academic Editors: Fernando Pérez-Rodríguez, Maria Schirone and Wojciech Kolanowski

Received: 26 June 2025

Revised: 18 August 2025

Accepted: 22 September 2025

Published: 5 November 2025

Citation: Carlino-Costa, C.; Belo, M.A.d.A. Ensuring Fish Safety Through Sustainable Aquaculture Practices. *Hygiene* **2025**, *5*, 51. <https://doi.org/10.3390/hygiene5040051>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: One Health; biosecurity; veterinary oversight; fish hygiene; food safety; green technologies

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 [3].

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 [1]. 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 [8–10].

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 (AMR), 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, antimicrobial stewardship, 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, through a One Health perspective.

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 vital to aquatic ecosystems, acting as integral links in the food chain and regulating biological interactions that keep these environments stable and healthy [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 addition to natural climatic influences, anthropogenic pollution from agriculture, industry, and urbanization is a critical factor of water quality deterioration that must be addressed in aquatic health management [15].

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 [16,17].

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 [18]. Integrated water quality management involves biological processes such as biofiltration and nitrification, which remove toxic compounds [13], as well as effluent treatment systems, including sedimentation tanks, constructed wetlands, and UV disinfection, that minimize environmental impact and enable safe water reuse [19].

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 [20]. 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 [21].

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 [22]. 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, RAS have emerged as a promising adaptation strategy [20,23]. 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 [23]. Commercial-scale applications include Atlantic salmon (*Salmo salar*) smolt and grow-out facilities in Norway [24], and intensive tilapia (*Oreochromis niloticus*) farming in China [25]. These operations have demonstrated that RAS can maintain high yields while reducing environmental impacts, even under challenging climatic or water availability conditions.

Because of their controlled and technically closed configuration, RAS present minimal ecological risks, including habitat degradation, eutrophication, biodiversity loss from escaped organisms, and the spread of pathogens or exotic species [23]. In addition, RAS are resilient to extreme climatic events such as droughts, floods, cyclones, salinity shifts, ocean acidification, and sea level rise, making them a stable alternative under environmental uncertainty [26]. Despite these advantages, their broader adoption is still constrained by high energy demand, associated greenhouse gas (GHG) emissions, and elevated implementation costs, particularly in developing countries [23,27,28]. To address these challenges, recent technological innovations include the integration of renewable energy sources (e.g., solar, wind, and biogas), high-efficiency pumps and filtration units, advanced oxygenation and aeration systems, and the incorporation of AI and IoT tools to optimize resource use and reduce operational costs. Parallel to these advances, several policy incentives are being implemented to facilitate the wider deployment of RAS in resource-limited contexts, such as targeted subsidies for clean energy adoption, green credit lines, tax reductions for sustainable technologies, and international development programs promoting climate-smart aquaculture.

The combination of these technological improvements and supportive policy frameworks is critical to making RAS more energy-efficient, cost-effective, and low-carbon. Such progress is essential for ensuring the resilience of aquaculture, meeting the global demand for safe, high-quality fish products, and contributing to long-term food security and environmental sustainability in the 21st century.

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 [28]. In RASs, efficient control of these compounds is essential to maintain optimal water conditions, safeguard fish health, and ensure the hygiene of the final product [29].

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) [30]. This conversion is crucial to avoid toxic water chemistry, reduce physiological stress, and prevent immune suppression or disease outbreaks. Commercial-scale examples include moving bed biofilm reactors (MBBRs) used in Atlantic salmon (*S. salar*) smolt production in Norway [31], trickling biofilters applied in tilapia (*O. niloticus*) farming in China [32], and fluidized sand filters in rainbow trout (*Oncorhynchus mykiss*) and Atlantic salmon (*S. salar*) production in the United States [33]. These systems consistently maintain low ammonia concentrations, enabling stable growth rates and high survival in intensive production environments.

To establish a functional nitrifying community, these bacteria typically form biofilms that adhere to high-surface-area substrates within the biofilter [34]. The formation, stability, and activity of these biofilms are regulated by quorum sensing mechanisms, which coordinate gene expression for biofilm development and nitrification [35]. 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 [36]. These consortia enhance system resilience and reduce dependence on water exchange, aligning with the principles of sustainable and resource-efficient aquaculture [28].

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 [35]. 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 [37]. Historically, the discharge of untreated wastewater has been associated with the spread of diseases across watersheds, prompting the global implementation of wastewater treatment technologies [38]. 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 [39].

Modern effluent treatment systems in aquaculture draw inspiration from natural biochemical, physical, and microbiological processes [40]. 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 [39]. 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 [19]. For example, membrane bioreactors are successfully applied in high-density Atlantic salmon (*S. salar*) to maintain low nutrient and microbial loads [41], whereas constructed wetlands are widely used in shrimp (*Litopenaeus vannamei*) farms for passive nutrient removal and sedimentation before water reuse [42].

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 [38]. 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 [40]. In rainbow trout (*O. mykiss*) RASs in Denmark, ultrafiltration combined with UV disinfection ensures consistent water quality for reuse [43].

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 [44,45]. 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 [46,47]. In closed-loop systems, such as RASs, 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 [40].

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 [48]. 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 [49]. In Australia, MAR is integrated with aquaculture effluent management, where treated water from inland fish farms is infiltrated into aquifers for later recovery and reuse in irrigation [50]. 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 [40].

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 [51]. 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 [52]. This nutrient recycling mechanism contributes to reducing environmental impacts, enhances overall system efficiency, and improves water quality, thereby supporting hygienic conditions and the health of farmed organisms [53]. A well-known example is the Canadian eastern aquaculture (salmon–kelp–mussel IMTA system), where salmon (*S. salar*) cages are integrated with blue mussels (*Mytilus edulis*) and kelp (*Saccharina latissima*) to capture particulate and dissolved nutrients, improving water quality and generating additional revenue streams [54]. Similarly, in Chile, salmon farms have successfully integrated the red alga *Gracilaria chilensis* and mussels to enhance nutrient removal [55].

IMTA systems address one of the core challenges in aquaculture: nutrient enrichment 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 [21]. This bioremediation function plays a crucial role in minimizing eutrophication risks and maintaining water clarity, both of which are fundamental for fish welfare and disease prevention [56]. In Italy's IMTA system, co-cultured sabellid polychaetes, sponges, and macroalgae demonstrate strong potential for biomass production and bioremediation in Mediterranean mariculture [57].

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 [58]. 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 [59]. According to Buck et al. [60], technological exchanges between Asia and the West have advanced aquaculture, with seaweed cultivation methods moving westward and the ecosystem services concept adopted in Asia. Bivalve farming, pioneered in Europe and New Zealand, has spread worldwide. For these authors, shifting seaweed and bivalve production offshore is seen as a way to reduce coastal pressures and supply large-scale biomass, with studies assessing its feasibility in open-ocean environments, sometimes integrated with offshore structures.

Despite these challenges, ongoing research indicates that integrating extractive species offshore can enhance nutrient capture and contribute to greater ecosystem services, including carbon sequestration and habitat provisioning [53]. 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 [61]. In Sanggou Bay, China, one of the world's largest IMTA sites, kelp, scallops, sea cucumbers, and fish are co-cultured over thousands of hectares, contributing substantially to local livelihoods and export markets [62].

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 [63].

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 [64]. 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 [63]. 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 [65]. In this context, sensing and automation technologies emerge as powerful tools to overcome these constraints. Intelligent sensors integrated with IoT platforms, AI, and automated response systems enable continuous and remote monitoring of key parameters such as temperature, dissolved oxygen, pH, turbidity, and nutrient concentrations. In practice, deployments use tools such as Aquacloud on IBM Cloud for data ingestion and prediction; LabVIEW HMIs with Java (MVC) back ends containerized in Docker; and telemetry via Arduino/SOAP over ZigBee or GPRS. For resilience, the application runs at the edge with optional cloud sync, ensuring alerts and actuation even under limited connectivity [66–68]. 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. For example, AI-driven aeration in recirculating aquaculture systems, using computer vision and biological energy modeling, enables precise oxygen control, reducing energy use by over 25% and accelerating growth [69].

Beyond water quality, these technologies enhance disease surveillance through biosensors and image-based diagnostics, enabling early detection and mitigation of outbreaks [70]. 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 [71]. In salmon aquaculture, smart feeders monitor feeding behavior and automatically adjust pellet distribution, reducing feed conversion ratios and improving growth performance [72].

Moreover, automation reduces the reliance on manual labor for routine tasks such as sampling, animal behavior observation, and parameter measurement [68]. This alleviates labor intensity while increasing consistency, accuracy, and productivity. Underwater cameras, machine vision systems, and motion capture technologies are increasingly used to monitor fish welfare, feeding activity, and system integrity with minimal human interference [70]. For instance, machine vision algorithms process live camera feeds to detect early signs of stress or abnormal swimming patterns, triggering alerts for immediate intervention [73].

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 [74]. When combined with big data analytics and AI, these technologies allow predictive modeling and automated decision-making, fostering adaptive and resilient farm management [75].

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 [76]. Disease outbreaks remain among the most significant challenges in fish farming, often resulting in substantial economic losses, compromised fish welfare, and reduced product quality [77]. Proactive and integrated health management strategies are critical to minimizing microbial contamination and ensuring the safety of fish for human consumption [77,78].

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* [78,79]. 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 [80].

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 [81,82]. 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 [83]. Complementarily, vaccination programs and the use of immunostimulants have been successfully applied in various aquaculture species to enhance resistance against specific pathogens [84].

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 [85]. 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 fish welfare, minimizing production losses, and safeguarding public health by reducing the risk of contaminated or unsafe seafood reaching consumers [1,3].

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 [83,86]. 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 [87].

Major transmission routes for pathogens include introduced animals such as brood-stock and fry, humans, vehicles, equipment, water sources, feed, and organic waste. To mitigate these risks, strict quarantine procedures are essential to ensure healthy introductions [88]. In addition, wireless sensor networks (WSNs) function as monitoring and early-warning tools, supporting biosecurity by enabling continuous tracking of environmental conditions and rapid detection of anomalies. Complementary measures such as strict access controls, personnel hygiene training, disinfection protocols, and sanitation further reduce cross-contamination risks [89].

Water treatment strategies, such as filtration, disinfection, and the use of RAS reduce pathogen load in the culture environment [46]. Proper feed handling is equally important

to minimize microbial contamination and pathogen transmission [89]. Moreover, effective waste management helps to prevent the proliferation of pathogens within production systems and their release into natural ecosystems [90]. 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 [91].

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 [92]. Real-time environmental sensor networks provide continuous, high-resolution monitoring of key water quality parameters linked to pathogen proliferation. Early detection of deviations from optimal ranges enables rapid, targeted interventions, thereby reducing outbreak risk and supporting timely, evidence-based disease management [93]. Big data analytics integrates multi-source datasets from farms, feed systems, and environmental sensors to reveal patterns linking environmental variability, pathogen incidence, and production outcomes. Such correlations enable predictive modeling and targeted interventions, strengthening biosecurity and reducing disease-related losses [94]. Machine learning improves disease forecasting by analyzing complex datasets from environmental, host health, and farm management records to detect outbreak risk with high precision, including subtle, non-linear links such as between temperature spikes and harmful algal blooms [95]. Remote sensing via satellites and drones monitors large-scale indicators like temperature gradients, chlorophyll-a, and sediment plumes, enabling early detection of pathogen-favorable conditions [93]. GIS integrates these data into real-time risk maps, guiding targeted actions such as adjusting stocking densities, refining water exchange, and applying localized biosecurity measures [96].

Looking ahead, future biosecurity strategies will likely emphasize integrated, risk-based approaches that combine preventive measures, technological innovations, and robust regulatory frameworks [97]. 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 [94]. 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 AMR in aquatic environments, affecting not only fish health but also posing significant threats to food safety and public health [98].

One of the main consequences of antibiotic residues and resistant bacteria in sediments and water columns is primarily attributed to therapeutic applications in aquaculture [99,100]. 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 [101]. In response, the development and implementation of vaccines have gained traction as a sustainable and preventive alternative [102]. Unlike antibiotics, vaccines do not leave residues, do not promote resistance, and can offer long-lasting immunity against specific pathogens [103].

While vaccination in aquatic environments indeed presents logistical challenges, including the risk of fish mortality due to handling stress or environmental fluctuations

during the process, field experience and research have demonstrated that such risks can be mitigated through refined protocols, optimized equipment, and trained personnel [104]. Successful large-scale vaccination campaigns have already been implemented in commercial aquaculture, resulting in significant reductions in disease incidence and antibiotic use [102]. Although adoption rates vary among species and regions due to economic and technical constraints, ongoing advances in vaccine formulation, delivery systems (e.g., oral, immersion, nanoparticle-based), and automation of vaccination procedures are steadily improving feasibility and cost-effectiveness [105]. Given the increasing regulatory and market pressures to reduce antimicrobial use, it is reasonable to anticipate that vaccination, alongside other biosecurity measures, will play an increasingly central role in mainstream preventive health management in aquaculture over the coming years [106].

Several vaccine types have been developed using advanced biotechnological methods, such as inactivated, live-attenuated, subunit, recombinant protein, and DNA-based vaccines [107]. 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 [84,107]. 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 [108].

Commercially available vaccines remain limited for several economically important aquaculture species, especially those with complex immune responses or diverse farming conditions [109]. In addition, regulatory, financial, and technical challenges continue to hinder the widespread adoption of promising experimental vaccines in practical field applications [108]. 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 [110,111].

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 [102,111]. 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 [108,112]. 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 AMR 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 [113,114].

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 [115]. 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 [116].

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 [117,118]. Prebiotics, such as fructooligosaccharides (FOS) and mannanoligosaccharides (MOS), act as selective substrates for beneficial bacteria and further support innate immunity in fish [119,120].

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 [121]. 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 [122]. Maintaining the health of aquatic animals requires the proactive control of water quality, sediment dynamics, and waste accumulation [69]. 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 [123].

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 [124]. 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 [122]. 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 [125,126]. 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 [127,128]. 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 [129]. Predictions indicate that water consumption for aquaculture may more than double by 2050, accompanied by increasing demand for terrestrial feed ingredients [130]. Improper site selection and conversion of sensitive habitats, such as mangroves and wetlands, to aquaculture facilities have already led to severe ecological consequences, including the depletion of wild brood stocks and irreversible biodiversity loss [131]. These impacts are not typically associated with rice paddy ecological aquaculture, which is well-documented for supporting biodiversity, enhancing nutrient cycling, and minimizing chemical use, making it a widely cited example of sustainable aquaculture practice [132]. 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 [133,134]. 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 [93]. 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 [135,136].

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 [137]. 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 [93,138,139].

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 [93]. 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 [136].

Future advances in early disease detection will focus on two main technologies: 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 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 [70,86,93]. Although eDNA remains the most sensitive option, cost-effective methods such as rapid diagnostic tests, routine monitoring of water quality indicators, and farmer-led syndromic surveillance can provide reliable early warnings and, when integrated into tiered monitoring frameworks, enhance disease detection in small-scale aquaculture systems [140,141].

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 [142]. Environmental conditions, species behavior, and production intensity all influence disease dynamics and diagnostic feasibility [137]. 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

Addressing these barriers will require the development of internationally harmonized data standards, improved platform interoperability, and affordable, user-friendly solutions, supported by collaborative engagement across all stakeholders in the aquaculture supply chain [143], yet their indiscriminate or prophylactic use raises major concerns about AMR, environmental contamination, and food safety [102,144]. Misuse, often without veterinary oversight, results in subtherapeutic exposure, resistant bacterial strains, and persistent residues in aquatic environments and fish tissues [145–147]. AMR poses a One Health challenge, as resistance genes (e.g., *tet*, *bla*, *sul*, *qnr*) spread through aquatic ecosystems and the food chain [148–153], while residues of antibiotics such as sulfamethazine, oxytetracycline, and tetracycline are detected in water, sediments, and edible tissues, sometimes above regulatory thresholds [154]. Other agents, including formalin, malachite green, and chloramine-T, are effective but carry toxicological risks [155,156].

Minimizing AMR requires strict regulation of antibiotic use, routine residue monitoring, and adoption of alternative tools such as vaccines, probiotics, phage therapy, and quorum-sensing inhibitors [53,64,81,84,119,157]. RAS reduce environmental discharge but can harbor AMR in biofilms [119,130,158–161]. Additional mitigation measures include water disinfection (UV, ozone), improved sludge treatment, and harmonized AMR surveillance, particularly in low- and middle-income countries [162–164].

Compliance with withdrawal periods is essential to prevent antimicrobial residues in fish intended for human consumption. These periods, defined by Codex, EMA, and WOA, ensure drug concentrations fall below Maximum Residue Limits (MRLs) [165–168]. Non-compliance can cause allergic reactions, toxicity, and AMR spread [168,169], and the use of prohibited substances such as chloramphenicol and nitrofurazone remains a concern [170]. Harmonization of MRLs is limited, and some developing countries lack specific regulations [168,171,172]. Monitoring programs, record-keeping, and digital tracking tools support compliance and protect market access [90].

Monitoring and environmental considerations are integral to sustainable aquaculture. Robust pharmacovigilance and traceability enhance regulatory oversight, allow

early detection of adverse drug reactions, and ensure transparency [173–176]. Since veterinary drugs can persist in sediments and affect non-target organisms [177,178], effluent treatment, sediment management, and the use of biodegradable formulations are recommended [48,179,180]. Integrating responsible drug use, biosecurity, alternative therapies, and environmental safeguards aligns aquaculture with One Health principles, supporting sustainability, food safety, and industry credibility.

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 [181].

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 [182,183]. Hence, the use of species-specific, bioavailable, and functionally effective feed components is central to responsible fish farming [184,185].

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 [181,186]. 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 [183].

5.1. Nutritional Formulation and Fish Physiology

Fish nutritional needs vary with species, digestive physiology, feeding habits, and developmental stage, making tailored formulations essential for sustainable production [187]. Proteins are the primary structural and functional components, supplying essential amino acids such as lysine, methionine, and threonine, with higher requirements in carnivores and early stages. Balanced amino acid profiles are achieved by combining animal sources (e.g., fish meal) and plant sources (e.g., soybean meal), often with supplementation [188]. Lipids provide concentrated energy and essential fatty acids, including omega-6 (linoleic) and omega-3 (linolenic, EPA, DHA), vital for membrane integrity, immunity, reproduction, and growth. Proper inclusion of animal and vegetable oils improves performance and omega-3 content [189–191]. Carbohydrates, though non-essential, are cost-effective energy sources and improve pellet stability, with utilization efficiency varying from low in carnivores to high in omnivores and herbivores [188,192,193].

Vitamins and minerals, though required in small amounts, are critical for immunity, metabolism, bone health, and reproduction. Antioxidants like vitamins C and E enhance disease resistance, while minerals such as phosphorus, calcium, and magnesium must be supplied in bioavailable forms, especially in intensive systems [194–197]. With the reduced reliance on fishmeal and fish oil, alternatives such as plant proteins, insects, microbial biomass, and agro-industrial byproducts are being assessed for digestibility and nutrient quality [198]. Functional additives (e.g., β -glucans, nucleotides, pigments) can improve immune function, stress tolerance, and feed efficiency [199,200]. Aligning feed formulation with feeding behavior minimizes waste, while phytase supplementation enhances phosphorus utilization and reduces environmental impact [201,202].

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 [183].

Ingredient digestibility determines the fraction of nutrients effectively absorbed by the animals, while palatability directly impacts feed intake [203]. 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* [204–208]. 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 [209].

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 [210]. 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 [102].

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 [211].

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 [212]. According to Auzins et al. [213], black soldier fly larvae (BSFL) meal represents a sustainable alternative protein source for aquafeeds, offering high nutritional value and the advantage of being reared on organic side-streams with low land and water requirements. Nonetheless, its large-scale economic viability remains a challenge. For these authors, production is still concentrated at experimental or pilot levels, with substantial capital and operational costs, and current market prices remain high, limiting competitiveness against

conventional fishmeal. 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 [44,214,215]. Microbial biomass, particularly single-cell proteins produced via precision fermentation, is emerging as a sustainable alternative for aquafeeds. Yeast- and bacterial-derived products have demonstrated favorable amino acid profiles along with immunomodulatory benefits for farmed fish. For example, KnipBio's "KnipBio Meal" (KBM), a yeast-based protein ingredient, has been granted GRAS (Generally Recognized as Safe) status by the FDA (US), which not only confirms its safety but also facilitates greater commercial adoption and market acceptance [216]. 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 [217]. 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 [218,219]. 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 [220].

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 [221]. 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 [222]. 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 [223–225]. 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 [226]. Moreover, integrating polyculture or multi-trophic aquaculture systems can increase protein yield per unit of input while providing ecological benefits such as nutrient bioremediation [221].

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 [227].

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 [200].

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 [228–230]. 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 [231,232]. 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) [233]. 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*) [230–234].

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 [227].

Despite the benefits, some immunostimulants may cause immunosuppression if used in excess, and their long-term effects remain underexplored [235]. 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 histamine caused by spoilage bacteria make the control of both pathogenic and spoilage microorganisms critical for fish product safety [236]. Therefore, integrating hygienic and sustainable protocols during harvest and post-harvest is essential for delivering safe aquaculture products to consumers [237,238].

6.1. Pre-Slaughter Management and Stress Reduction

Minimizing stress before slaughter not only supports animal welfare but also preserves meat quality by preventing the rapid exhaustion of energy stores, excessive lactic acid production, a decline in muscle pH, and premature rigor mortis [239,240]. According to Vijayan et al. [241], tilapia (*Oreochromis mossambicus*) subjected to 2 h of confinement stress showed increased glucose and lactate levels, reflecting heightened carbohydrate metabolism. Longer exposure to stress (24 h) 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. [239], two types of metabolic responses may occur in fish muscle post-mortem due to stress or cortisol exposure. Short-term, intense stress just before slaughter results in lactic acid production and lowered pH from enhanced anaerobic glycolysis. In contrast, prolonged or repeated 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 [242], gentle handling [239,243], low stocking density during transport [244], and the use of anesthetics or sedation [245], 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 [246]. Exsanguination should follow humane stunning techniques (e.g., percussive, electrical, or immersion in anesthetics) to reduce suffering and preserve fillet quality [247]. Live chilling, which entails the rapid reduction in body temperature in fish, is commonly employed as a pre-slaughter procedure, particularly for tropical species [248]. 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 [249]. 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 [250].

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 [251]. 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 [252,253]. 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 [254].

In practice, electrical and percussive stunning represent the two most widely implemented humane methods in aquaculture globally. Electrical stunning is extensively

applied in Europe where regulatory frameworks such as EU Council Regulation (EC) No 1099/2009 enforce animal welfare at slaughter [247]. Conversely, its adoption in low- and middle-income countries remains limited due to high equipment costs, lack of trained personnel, and inadequate infrastructure [249]. Percussive stunning, though effective and comparatively cheaper, requires skilled operators and precise calibration, restricting its broader use in small- and medium-scale farms [246,250]. Species-specific differences in anatomy further complicate standardization across diverse aquaculture systems [254].

The primary barriers to the wider adoption of humane stunning methods include (i) economic constraints related to equipment and maintenance [255]; (ii) limited access to modern slaughter facilities in many developing regions [256]; (iii) variability in fish anatomy that challenges effective application [254]; and (iv) uneven regulatory enforcement, with export-oriented industries (e.g., European salmon) being more compliant than local markets [246]. These constraints highlight the gap between welfare-oriented practices promoted by international guidelines and their practical implementation in diverse production contexts.

On the other hand, maintaining strict sanitary conditions during fish processing is essential to ensure food safety and product quality [255]. 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 [256].

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 [237]. 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 [257], use of solar-powered coolers [258,259], and eco-friendly packaging materials [260] 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 [261].

6.4. Packaging

Appropriate packaging extends shelf life and prevents microbial ingress [262]. 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 [263,264]. The process involves enclosing the product in a low-oxygen-permeable material and hermetically sealing it following air evacuation [264]. 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 [263].

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 [265].

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 [266]. 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 [3,267].

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 [268,269]. 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 [270]. 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 [269,271].

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 [94,272]. 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 [273]. Sensors integrated into water systems can continuously measure temperature, dissolved oxygen, ammonia, pH, and turbidity [274]. These parameters are critical in preventing microbial growth, minimizing stress-induced immunosuppression in fish, and reducing the incidence of opportunistic infections [275]. Continuous IoT monitoring of key parameters (temperature, dissolved oxygen, pH, turbidity) enables predictive management and fast correction of out-of-range values; when these data are analyzed with Machine Learning models (e.g., Random Forest) and optimized via the Quantum Approximate Optimization Algorithm (QAOA) to reduce training time by ~50%, water-quality monitoring and forecasting in aquaculture become more accurate and responsive [276].

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 [94,277]. By systematically identifying microbial hazards, these assessments support HACCP implementation and facilitate proactive risk management across the production chain [236,277]. 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 [236]. 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) [271,278–281]. These substances can accumulate in aquatic organisms due to environmental pollution or the use of contaminated feeds [282]. 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 [283] 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 [284]. 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 [269,285]. 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 [286].

Barcoding, particularly DNA barcoding, enables precise species identification, reducing cases of mislabeling and fraud [287,288]. 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 [289]. 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 [290]. This enhances transparency and trust among producers, regulators, retailers, and consumers [269,285].

However, the widespread adoption of blockchain in aquaculture supply chains still faces practical challenges. These include the lack of standardized data formats across different actors, which complicates integration and comparability of records across borders [283,284]. Interoperability issues between blockchain platforms and legacy supply chain management systems remain a major limitation, as most operators employ heterogeneous digital tools that are not yet harmonized with blockchain infrastructures [285,286]. In addition, stakeholder adoption is constrained, particularly among small- and medium-sized enterprises (SMEs), due to high implementation costs, technical complexity, and limited digital literacy, which hinder accessibility in resource-limited contexts [286,287]. Addressing these barriers will require the development of internationally harmonized data standards, improved platform interoperability, and affordable, user-friendly solutions, supported by collaborative engagement across all stakeholders in the aquaculture supply chain [283,287].

Collectively, these technologies support food safety, biosecurity, and sustainability objectives by improving the accountability and responsiveness of the aquaculture supply chain [269,285,287]. 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 [291]. 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 [292].

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 WHO, and the WOA. These standards are crucial for harmonizing food safety criteria, especially for countries engaged in fish export [293].

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 MRLs for veterinary drugs, water quality parameters, and pathogen control in processing plants, directly impacting the hygienic quality of the final product [90].

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 [177]. This regulatory process ensures that only authorized substances, with proven safety, efficacy, and environmental compatibility, are employed in aquatic food production systems [294]. 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 [168]. Regulatory agencies, such as the 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 [295]; Monitoring the emergence of AMR [280]; Ensuring adherence to Good Aquaculture Practices (GAPs) [296]. 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 [297]. 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 [298]. 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); and 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 [299].

Comparatively, the ASC program is often regarded as the most stringent, with strong emphasis on environmental sustainability and social responsibility [300], whereas GlobalG.A.P. focuses more on harmonizing good agricultural and aquaculture practices to improve farm-level management and traceability [301]. BAP adopts a tiered certification approach (farm, hatchery, feed mill, and processing plant), making it comprehensive across the value chain but generally perceived as more industry-driven [301]. In contrast, Organic Standards (EU Organic, USDA Organic) are more restrictive in feed inputs and chemical

use, strongly appealing to niche consumer markets but limiting scalability in intensive aquaculture systems [302]. These differences shape not only compliance costs for producers but also consumer perception and market access, with ASC and Organic labels typically commanding stronger recognition in premium markets, while GlobalG.A.P. and BAP offer broader adoption and supply chain integration [301].

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 [303].

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 [304]. These audits evaluate facility sanitation, handling procedures, water quality logs, cold chain management, and worker hygiene practices [305]. 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. To support these efforts, policy measures should prioritize mandatory training for producers in hygiene and biosecurity, enforce compliance with withdrawal periods and Maximum Residue Limits (MRLs), incentivize the adoption of environmentally friendly inputs, and expand AMR surveillance programs. Governments and industry bodies should also promote investment in closed or semi-closed production systems, enhance waste and effluent treatment standards, and strengthen traceability through digital platforms to ensure transparency across the value chain.

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.

Author Contributions: Conceptualization, C.C.-C. and M.A.d.A.B.; methodology, C.C.-C. and M.A.d.A.B.; investigation, C.C.-C. and M.A.d.A.B.; writing—original draft preparation, C.C.-C.; writing—review and editing, M.A.d.A.B.; visualization, C.C.-C.; supervision, M.A.d.A.B.; project administration, M.A.d.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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	Mannan oligosaccharides
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 Organization for Animal Health
WSNs	Wireless Sensor Networks
WTO	World Trade Organization

References

1. FAO. *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation*; FAO: Rome, Italy, 2022; p. 1176. [\[CrossRef\]](#)
2. FAO; IFAD; UNICEF; WFP; WHO. *The State of Food Security and Nutrition in the World 2024—Financing to End Hunger, 1178 Food Insecurity and Malnutrition in All Its Forms*; FAO: Rome, Italy, 2024. [\[CrossRef\]](#)
3. Jennings, S.; Stentiford, G.D.; Leocadio, A.M.; Jeffery, K.R.; Metcalfe, J.D.; Katsiadaki, I.; Auchterlonie, N.A.; Mangi, S.C.; Pinnegar, J.K.; Ellis, T. Aquatic Food Security: Insights into Challenges and Solutions from an Analysis of Interactions between Fisheries, Aquaculture, Food Safety, Human Health, Fish and Human Welfare, Economy and Environment. *Fish Fish.* **2016**, *17*, 893–938. [\[CrossRef\]](#)
4. Cojocar, A.L.; Liu, Y.; Smith, M.D.; Akpalu, W.; Chávez, C.; Dey, M.M.; Dresdner, J.; Kahui, V.; Pincinato, R.B.; Tran, N. The “Seafood” System: Aquatic Foods, Food Security, and the Global South. *Rev. Environ. Econ. Policy* **2022**, *16*, 306–326. [\[CrossRef\]](#)
5. Bjørndal, T.; Dey, M.; Tusvik, A. Economic Analysis of the Contributions of Aquaculture to Future Food Security. *Aquaculture* **2024**, *578*, 740071. [\[CrossRef\]](#)
6. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; A/RES/70/1; United Nations: New York, NY, USA, 2015.
7. Adewale, O.; Liverpool-Tasie, L.S.O. *Guidelines for Good Hygienic Practices for Fish and Fish Products*; Michigan State University: East Lansing, MI, USA, 2023.
8. Bunting, S.W. *Principles of Sustainable Aquaculture: Promoting Social, Economic and Environmental Resilience*; Routledge: Milton Park, UK, 2024; ISBN 1-003-34282-5.
9. Pinto Ferreira, J.; Battaglia, D.; Dorado García, A.; Tempelman, K.; Bullon, C.; Motriuc, N.; Caudell, M.; Cahill, S.; Song, J.; LeJeune, J. Achieving Antimicrobial Stewardship on the Global Scale: Challenges and Opportunities. *Microorganisms* **2022**, *10*, 1599. [\[CrossRef\]](#)
10. Bedane, T.D.; Agga, G.E.; Gutema, F.D. Hygienic Assessment of Fish Handling Practices along Production and Supply Chain and Its Public Health Implications in Central Oromia, Ethiopia. *Sci. Rep.* **2022**, *12*, 13910. [\[CrossRef\]](#)
11. Boyd, C.E.; Tucker, C.S. *Pond Aquaculture Water Quality Management*; Springer Science & Business Media: Berlin, Germany, 2012; ISBN 1-4615-5407-1.
12. Craig, C.A.; Kollaus, K.A.; Behen, K.P.; Bonner, T.H. Relationships among Spring Flow, Habitats, and Fishes within Evolutionary Refugia of the Edwards Plateau. *Ecosphere* **2016**, *7*, e01205. [\[CrossRef\]](#)
13. Yusoff, F.M.; Umi, W.A.; Ramli, N.M.; Harun, R. Water Quality Management in Aquaculture. *Camb. Prism. Water* **2024**, *2*, e8. [\[CrossRef\]](#)
14. Assefa, A.; Abunna, F. Maintenance of Fish Health in Aquaculture: Review of Epidemiological Approaches for Prevention and Control of Infectious Disease of Fish. *Vet. Med. Int.* **2018**, *2018*, 5432497. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various Natural and Anthropogenic Factors Responsible for Water Quality Degradation: A Review. *Water* **2021**, *13*, 2660. [\[CrossRef\]](#)
16. Guo, X.; Huang, M.; Luo, X.; You, W.; Ke, C. Impact of Ocean Acidification on Shells of the Abalone Species *Haliotis Diversicolor* and *Haliotis Discus Hannai*. *Mar. Environ. Res.* **2023**, *192*, 106183. [\[CrossRef\]](#)
17. Lusiastuti, A.M.; Prayitno, S.B.; Sugiani, D.; Caruso, D. Building and Improving the Capacity of Fish and Environmental Health Management Strategy in Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *521*, 012016.
18. Hassan, S.M.; Rashid, M.S.; Muhaimeed, A.R.; Madlul, N.S.; Al-Katib, M.U.; Sulaiman, M.A. Effect of New Filtration Medias on Water Quality, Biomass, Blood Parameters and Plasma Biochemistry of Common Carp (*Cyprinus carpio*) in RAS. *Aquaculture* **2022**, *548*, 737630. [\[CrossRef\]](#)
19. Tom, A.P.; Jayakumar, J.S.; Biju, M.; Somarajan, J.; Ibrahim, M.A. Aquaculture Wastewater Treatment Technologies and Their Sustainability: A Review. *Energy Nexus* **2021**, *4*, 100022. [\[CrossRef\]](#)
20. Ahmed, N.; Turchini, G.M. Recirculating Aquaculture Systems (RAS): Environmental Solution and Climate Change Adaptation. *J. Clean. Prod.* **2021**, *297*, 126604. [\[CrossRef\]](#)
21. Troell, M.; Joyce, A.; Chopin, T.; Neori, A.; Buschmann, A.H.; Fang, J.-G. Ecological Engineering in Aquaculture—Potential for Integrated Multi-Trophic Aquaculture (IMTA) in Marine Offshore Systems. *Aquaculture* **2009**, *297*, 1–9. [\[CrossRef\]](#)
22. Tzu, N.L.; Farha, W.A.R.W.E.; Musa, N.; Rifqi, M.M.; Hidayati, S.; Pratiwi, H.; Aris, N.A.M.; Musa, N.; Rasid, R.; Abd Aziz, M.F.H. Sensing Technologies and Automation: Revolutionizing Aquaculture Towards Sustainability and Resilience. *Semarak Int. J. Agric. For. Fish.* **2024**, *1*, 10–18.

23. Badiola, M.; Mendiola, D.; Bostock, J. Recirculating Aquaculture Systems (RAS) Analysis: Main Issues on Management and Future Challenges. *Aquac. Eng.* **2012**, *51*, 26–35. [\[CrossRef\]](#)
24. Dalsgaard, J.; Lund, I.; Thorarindottir, R.; Drengstig, A.; Arvonen, K.; Pedersen, P.B. Farming Different Species in RAS in Nordic Countries: Current Status and Future Perspectives. *Aquac. Eng.* **2013**, *53*, 2–13. [\[CrossRef\]](#)
25. Luo, G.; Gao, Q.; Wang, C.; Liu, W.; Sun, D.; Li, L.; Tan, H. Growth, Digestive Activity, Welfare, and Partial Cost-Effectiveness of Genetically Improved Farmed Tilapia (*Oreochromis niloticus*) Cultured in a Recirculating Aquaculture System and an Indoor Biofloc System. *Aquaculture* **2014**, *422*, 1–7. [\[CrossRef\]](#)
26. Ahmed, N.; Thompson, S.; Glaser, M. Global Aquaculture Productivity, Environmental Sustainability, and Climate Change Adaptability. *Environ. Manag.* **2019**, *63*, 159–172. [\[CrossRef\]](#)
27. Helfrich, L.A.; Libey, G.S. *Fish Farming in Recirculating Aquaculture Systems (RAS)*; Virginia Cooperative Extension: Yorktown, VA, USA, 1991.
28. Zhang, S.-Y.; Li, G.; Wu, H.-B.; Liu, X.-G.; Yao, Y.-H.; Tao, L.; Liu, H. An Integrated Recirculating Aquaculture System (RAS) for Land-Based Fish Farming: The Effects on Water Quality and Fish Production. *Aquac. Eng.* **2011**, *45*, 93–102. [\[CrossRef\]](#)
29. Ruiz, P.; Vidal, J.M.; Sepúlveda, D.; Torres, C.; Villouta, G.; Carrasco, C.; Aguilera, F.; Ruiz-Tagle, N.; Urrutia, H. Overview and Future Perspectives of Nitrifying Bacteria on Biofilters for Recirculating Aquaculture Systems. *Rev. Aquac.* **2020**, *12*, 1478–1494. [\[CrossRef\]](#)
30. Brown, A.R.; Wilson, R.W.; Tyler, C.R. Assessing the Benefits and Challenges of Recirculating Aquaculture Systems (RAS) for Atlantic Salmon Production. *Rev. Fish. Sci. Aquac.* **2024**, *33*, 380–401. [\[CrossRef\]](#)
31. Stenhaus, S.R. *The Effect of Organic Load on the Rearing Water and Biofilter Biofilm Microbiota Across the Freshwater and Brackish Water Phases in RAS with Atlantic Salmon (Salmo salar)*; NTNU: Trondheim, Norway, 2023.
32. Wang, C.-Y.; Chang, C.-Y.; Dahms, H.-U.; Lai, H.-T. Effects of Stocking Density of Tilapia on the Performance of a Membrane Filtration–Recirculating Aquaponic System. *Desalination Water Treat.* **2017**, *96*, 22–32. [\[CrossRef\]](#)
33. Tsukuda, S.; Christianson, L.; Kolb, A.; Saito, K.; Summerfelt, S. Heterotrophic Denitrification of Aquaculture Effluent Using Fluidized Sand Biofilters. *Aquac. Eng.* **2015**, *64*, 49–59. [\[CrossRef\]](#)
34. Crab, R.; Avnimelech, Y.; Defoirdt, T.; Bossier, P.; Verstraete, W. Nitrogen Removal Techniques in Aquaculture for a Sustainable Production. *Aquaculture* **2007**, *270*, 1–14. [\[CrossRef\]](#)
35. Sugita, H.; Nakamura, H.; Shimada, T. Microbial Communities Associated with Filter Materials in Recirculating Aquaculture Systems of Freshwater Fish. *Aquaculture* **2005**, *243*, 403–409. [\[CrossRef\]](#)
36. Xavier, K.B.; Bassler, B.L. LuxS Quorum Sensing: More than Just a Numbers Game. *Curr. Opin. Microbiol.* **2003**, *6*, 191–197. [\[CrossRef\]](#)
37. Jin, D.; Zhang, X.; Zhang, X.; Zhou, L.; Zhu, Z.; Deogratias, U.K.; Wu, Z.; Zhang, K.; Ji, X.; Ju, T. A Critical Review of Comammox and Synergistic Nitrogen Removal Coupling Anammox: Mechanisms and Regulatory Strategies. *Sci. Total Environ.* **2024**, *948*, 174855. [\[CrossRef\]](#)
38. Boyd, C.E. Guidelines for Aquaculture Effluent Management at the Farm-Level. *Aquaculture* **2003**, *226*, 101–112. [\[CrossRef\]](#)
39. Bryan, F.L. Diseases Transmitted by Foods Contaminated by Wastewater. *J. Food Prot.* **1977**, *40*, 45–56. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Salgot, M.; Folch, M. Wastewater Treatment and Water Reuse. *Curr. Opin. Environ. Sci. Health* **2018**, *2*, 64–74. [\[CrossRef\]](#)
41. Bao, W.; Zhu, S.; Jin, G.; Ye, Z. Generation, Characterization, Perniciousness, Removal and Reutilization of Solids in Aquaculture Water: A Review from the Whole Process Perspective. *Rev. Aquac.* **2019**, *11*, 1342–1366. [\[CrossRef\]](#)
42. Tilley, D.R.; Badrinarayanan, H.; Rosati, R.; Son, J. Constructed Wetlands as Recirculation Filters in Large-Scale Shrimp Aquaculture. *Aquac. Eng.* **2002**, *26*, 81–109. [\[CrossRef\]](#)
43. de Jesus Gregersen, K.J.; Pedersen, P.B.; Pedersen, L.-F.; Liu, D.; Dalsgaard, J. UV Irradiation and Micro Filtration Effects on Micro Particle Development and Microbial Water Quality in Recirculation Aquaculture Systems. *Aquaculture* **2020**, *518*, 734785. [\[CrossRef\]](#)
44. Ahmad, A.; Hassan, S.W.; Banat, F. An Overview of Microalgae Biomass as a Sustainable Aquaculture Feed Ingredient: Food Security and Circular Economy. *Bioengineered* **2022**, *13*, 9521–9547. [\[CrossRef\]](#)
45. de Campos, S.X.; Soto, M. The Use of Constructed Wetlands to Treat Effluents for Water Reuse. *Environments* **2024**, *11*, 35. [\[CrossRef\]](#)
46. Liberti, L.; Notarnicola, M.; Petruzzelli, D. Advanced Treatment for Municipal Wastewater Reuse in Agriculture. UV Disinfection: Parasite Removal and by-Product Formation. *Desalination* **2003**, *152*, 315–324. [\[CrossRef\]](#)
47. Collivignarelli, M.C.; Abbà, A.; Miino, M.C.; Caccamo, F.M.; Torretta, V.; Rada, E.C.; Sorlini, S. Disinfection of Wastewater by UV-Based Treatment for Reuse in a Circular Economy Perspective. Where Are We At? *Int. J. Environ. Res. Public Health* **2021**, *18*, 77. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Jeffrey, P.; Yang, Z.; Judd, S.J. The Status of Potable Water Reuse Implementation. *Water Res.* **2022**, *214*, 118198. [\[CrossRef\]](#) [\[PubMed\]](#)

49. Yuan, J.; Van Dyke, M.I.; Huck, P.M. Water Reuse through Managed Aquifer Recharge (MAR): Assessment of Regulations/Guidelines and Case Studies. *Water Qual. Res. J. Can.* **2016**, *51*, 357–376. [\[CrossRef\]](#)
50. Page, D.; Vanderzalm, J.; Gonzalez, D.; Bennett, J.; Castellazzi, P. Managed Aquifer Recharge for Agriculture in Australia—History, Success Factors and Future Implementation. *Agric. Water Manag.* **2023**, *285*, 108382. [\[CrossRef\]](#)
51. Shitu, A.; Liu, G.; Muhammad, A.I.; Zhang, Y.; Tadda, M.A.; Qi, W.; Liu, D.; Ye, Z.; Zhu, S. Recent Advances in Application of Moving Bed Bioreactors for Wastewater Treatment from Recirculating Aquaculture Systems: A Review. *Aquac. Fish.* **2022**, *7*, 244–258. [\[CrossRef\]](#)
52. Neori, A.; Chopin, T.; Troell, M.; Buschmann, A.H.; Kraemer, G.P.; Halling, C.; Shpigel, M.; Yarish, C. Integrated Aquaculture: Rationale, Evolution and State of the Art Emphasizing Seaweed Biofiltration in Modern Mariculture. *Aquaculture* **2004**, *231*, 361–391. [\[CrossRef\]](#)
53. Buck, B.H.; Troell, M.F.; Krause, G.; Angel, D.L.; Grote, B.; Chopin, T. State of the Art and Challenges for Offshore Integrated Multi-Trophic Aquaculture (IMTA). *Front. Mar. Sci.* **2018**, *5*, 165. [\[CrossRef\]](#)
54. Carras, M.A.; Knowler, D.; Pearce, C.M.; Hamer, A.; Chopin, T.; Weaire, T. A Discounted Cash-Flow Analysis of Salmon Monoculture and Integrated Multi-Trophic Aquaculture in Eastern Canada. *Aquac. Econ. Manag.* **2020**, *24*, 43–63. [\[CrossRef\]](#)
55. Buschmann, A.H.; Cabello, F.; Young, K.; Carvajal, J.; Varela, D.A.; Henríquez, L. Salmon Aquaculture and Coastal Ecosystem Health in Chile: Analysis of Regulations, Environmental Impacts and Bioremediation Systems. *Ocean Coast. Manag.* **2009**, *52*, 243–249. [\[CrossRef\]](#)
56. Fernandez-Gonzalez, V.; Toledo-Guedes, K.; Valero-Rodriguez, J.M.; Agraso, M.d.M.; Sanchez-Jerez, P. Harvesting Amphipods Applying the Integrated Multitrophic Aquaculture (IMTA) Concept in off-Shore Areas. *Aquaculture* **2018**, *489*, 62–69. [\[CrossRef\]](#)
57. Giangrande, A.; Pierri, C.; Arduini, D.; Borghese, J.; Licciano, M.; Trani, R.; Corriero, G.; Basile, G.; Cecere, E.; Petrocelli, A. An Innovative IMTA System: Polychaetes, Sponges and Macroalgae Co-Cultured in a Southern Italian in-Shore Mariculture Plant (Ionian Sea). *J. Mar. Sci. Eng.* **2020**, *8*, 733. [\[CrossRef\]](#)
58. Lamprianidou, F.; Telfer, T.; Ross, L.G. A Model for Optimization of the Productivity and Bioremediation Efficiency of Marine Integrated Multitrophic Aquaculture. *Estuar. Coast. Shelf Sci.* **2015**, *164*, 253–264. [\[CrossRef\]](#)
59. Gentry, R.R.; Froehlich, H.E.; Grimm, D.; Kareiva, P.; Parke, M.; Rust, M.; Gaines, S.D.; Halpern, B.S. Mapping the Global Potential for Marine Aquaculture. *Nat. Ecol. Evol.* **2017**, *1*, 1317–1324. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Buck, B.H.; Nevejan, N.; Wille, M.; Chambers, M.D.; Chopin, T. Offshore and Multi-Use Aquaculture with Extractive Species: Seaweeds and Bivalves. In *Aquaculture Perspective of Multi-Use Sites in the Open Ocean: The Untapped Potential for Marine Resources in the Anthropocene*; Springer International Publishing: Cham, Switzerland, 2017; pp. 23–69.
61. North, W.J. Oceanic Farming of Macrocystis, the Problems and Non-Problems. In *Developments in Aquaculture and Fisheries Science (Netherlands)*; Elsevier: Amsterdam, The Netherlands, 1987.
62. Fang, J.; Zhang, J.; Xiao, T.; Huang, D.; Liu, S. Integrated Multi-Trophic Aquaculture (IMTA) in Sanggou Bay, China. *Aquac. Environ. Interact.* **2016**, *8*, 201–205. [\[CrossRef\]](#)
63. Rosa, J.; Lemos, M.F.; Crespo, D.; Nunes, M.; Freitas, A.; Ramos, F.; Pardal, M.Â.; Leston, S. Integrated Multitrophic Aquaculture Systems—Potential Risks for Food Safety. *Trends Food Sci. Technol.* **2020**, *96*, 79–90. [\[CrossRef\]](#)
64. Zhu, Y.; Wang, N.; Wu, Z.; Chen, S.; Luo, J.; Christakos, G.; Wu, J. The Role of Seaweed Cultivation in Integrated Multi-Trophic Aquaculture (IMTA): The Current Status and Challenges. *Rev. Aquac.* **2025**, *17*, e70042. [\[CrossRef\]](#)
65. Boyd, C.E.; D’Abramo, L.R.; Glencross, B.D.; Huyben, D.C.; Juarez, L.M.; Lockwood, G.S.; McNevin, A.A.; Tacon, A.G.; Teletchea, F.; Tomasso, J.R., Jr. Achieving Sustainable Aquaculture: Historical and Current Perspectives and Future Needs and Challenges. *J. World Aquac. Soc.* **2020**, *51*, 578–633. [\[CrossRef\]](#)
66. Rastegari, H.; Nadi, F.; Lam, S.S.; Ikhwanuddin, M.; Kasan, N.A.; Rahmat, R.F.; Mahari, W.A.W. Internet of Things in Aquaculture: A Review of the Challenges and Potential Solutions Based on Current and Future Trends. *Smart Agric. Technol.* **2023**, *4*, 100187. [\[CrossRef\]](#)
67. Prapti, D.R.; Mohamed Shariff, A.R.; Che Man, H.; Ramli, N.M.; Perumal, T.; Shariff, M. Internet of Things (IoT)-based Aquaculture: An Overview of IoT Application on Water Quality Monitoring. *Rev. Aquac.* **2022**, *14*, 979–992. [\[CrossRef\]](#)
68. Mustapha, U.F.; Alhassan, A.-W.; Jiang, D.-N.; Li, G.-L. Sustainable Aquaculture Development: A Review on the Roles of Cloud Computing, Internet of Things and Artificial Intelligence (CIA). *Rev. Aquac.* **2021**, *13*, 2076–2091. [\[CrossRef\]](#)
69. Yang, J.; Zhou, Y.; Guo, Z.; Zhou, Y.; Shen, Y. Deep learning-based intelligent precise aeration strategy for factory recirculating aquaculture systems. *Artif. Intell. Agric.* **2024**, *12*, 57–71. [\[CrossRef\]](#)
70. Li, D.; Liu, C. Analysis and Future Prospects of Artificial Intelligence in Aquaculture. *Smart Agric.* **2020**, *2*, 1–20.
71. Mandal, A.; Ghosh, A.R. Role of Artificial Intelligence (AI) in Fish Growth and Health Status Monitoring: A Review on Sustainable Aquaculture. *Aquac. Int.* **2024**, *32*, 2791–2820. [\[CrossRef\]](#)
72. Føre, M.; Alver, M.O.; Frank, K.; Alfredsen, J.A. Advanced Technology in Aquaculture—Smart Feeding in Marine Fish Farms. In *Smart Livestock Nutrition*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 227–268.

73. Cui, M.; Liu, X.; Liu, H.; Zhao, J.; Li, D.; Wang, W. Fish Tracking, Counting, and Behaviour Analysis in Digital Aquaculture: A Comprehensive Survey. *Rev. Aquac.* **2025**, *17*, e13001. [\[CrossRef\]](#)
74. Huang, Y.-P.; Khabusi, S.P. Artificial Intelligence of Things (AIoT) Advances in Aquaculture: A Review. *Processes* **2025**, *13*, 73. [\[CrossRef\]](#)
75. Shi, B.; Sreeram, V.; Zhao, D.; Duan, S.; Jiang, J. A Wireless Sensor Network-Based Monitoring System for Freshwater Fishpond Aquaculture. *Biosyst. Eng.* **2018**, *172*, 57–66. [\[CrossRef\]](#)
76. Simbeye, D.S.; Yang, S.F. Water Quality Monitoring and Control for Aquaculture Based on Wireless Sensor Networks. *J. Netw.* **2014**, *9*, 840. [\[CrossRef\]](#)
77. Gudding, R.; Van Muiswinkel, W.B. A History of Fish Vaccination: Science-Based Disease Prevention in Aquaculture. *Fish Shellfish. Immunol.* **2013**, *35*, 1683–1688. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Nafiqoh, N.; Novita, H.; Sugiani, D.; Gardenia, L.; Taukhd, T.; Widyaningrum, A.; Susanti, D.R. *Aeromonas hydrophila* AHL 0905-2 and *Streptococcus agalactiae* N14G as Combined Vaccine Candidates for Nile Tilapia. *HAYATI J. Biosci.* **2022**, *29*, 137–145. [\[CrossRef\]](#)
79. Derome, N.; Gauthier, J.; Boutin, S.; Llewellyn, M. Bacterial Opportunistic Pathogens of Fish. In *The Rasputin Effect: When Commensals and Symbionts Become Parasitic*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 81–108.
80. Valladão, G.M.R.; Gallani, S.U.; Pilarski, F. South American Fish for Continental Aquaculture. *Rev. Aquac.* **2018**, *10*, 351–369. [\[CrossRef\]](#)
81. de Andrade Belo, M.A.; de Moraes, J.R.E.; Soares, V.E.; Martins, M.L.; Brum, C.D.; deMoraes, F.R. Vitamin C and Endogenous Cortisol in Foreign-Body Inflammatory Response in Pacus. *Pesqui. Agropecuária Bras.* **2012**, *47*, 1015–1021. [\[CrossRef\]](#)
82. Yasin, I.S.M.; Mohamad, A.; Azzam-Sayuti, M.; Saba, A.O.; Azmai, M.N.A. Disease Management in Aquaculture. *Manag. Fish Dis.* **2025**, 437–464. [\[CrossRef\]](#)
83. Muthu, M.P.; George, M.R.; John, R. Biosecurity Strategies in Aquaculture for Fish Health Management. *J. Aquac. Trop.* **2020**, *35*, 9–26.
84. Palić, D.; Scarfe, A.D.; Walster, C.I. A Standardized Approach for Meeting National and International Aquaculture Biosecurity Requirements for Preventing, Controlling, and Eradicating Infectious Diseases. *J. Appl. Aquac.* **2015**, *27*, 185–219. [\[CrossRef\]](#)
85. Hoebe, K.; Janssen, E.; Beutler, B. The Interface between Innate and Adaptive Immunity. *Nat. Immunol.* **2004**, *5*, 971–974. [\[CrossRef\]](#)
86. Bohara, K.; Joshi, P.; Acharya, K.P.; Ramena, G. Emerging Technologies Revolutionising Disease Diagnosis and Monitoring in Aquatic Animal Health. *Rev. Aquac.* **2024**, *16*, 836–854. [\[CrossRef\]](#)
87. Can, E.; Austin, B.; Steinberg, C.; Carboni, C.; Sağlam, N.; Thompson, K.; Yiğit, M.; Seyhaneyildiz Can, S.; Ergün, S. Best Practices for Fish Biosecurity, Well-Being and Sustainable Aquaculture. *Sustain. Aquat. Res.* **2023**, *2*, 221–267.
88. Murray, K.N.; Clark, T.S.; Kibus, M.J.; Kent, M.L. Specific Pathogen Free—A Review of Strategies in Agriculture, Aquaculture, and Laboratory Mammals and How They Inform New Recommendations for Laboratory Zebrafish. *Res. Vet. Sci.* **2022**, *142*, 78–93. [\[CrossRef\]](#)
89. Russell Danner, G.; Merrill, P. Disinfectants, Disinfection, and Biosecurity in Aquaculture. In *Aquaculture Biosecurity: Prevention, Control, and Eradication of Aquatic Animal Disease*; Wiley: Hoboken, NJ, USA, 2005; pp. 91–128.
90. Okocha, R.C.; Olatoye, I.O.; Adediji, O.B. Food Safety Impacts of Antimicrobial Use and Their Residues in Aquaculture. *Public Health Rev.* **2018**, *39*, 21. [\[CrossRef\]](#)
91. Dauda, A.B.; Ajadi, A.; Tola-Fabunmi, A.S.; Akinwale, A.O. Waste Production in Aquaculture: Sources, Components and Managements in Different Culture Systems. *Aquac. Fish.* **2019**, *4*, 81–88. [\[CrossRef\]](#)
92. Zepeda, C.; Jones, J.B.; Zagmutt, F.J. Compartmentalisation in Aquaculture Production Systems. *Rev. Sci. Tech. (Int. Off. Epizoot.)* **2008**, *27*, 229–241. [\[CrossRef\]](#)
93. MacAulay, S.; Ellison, A.R.; Kille, P.; Cable, J. Moving towards Improved Surveillance and Earlier Diagnosis of Aquatic Pathogens: From Traditional Methods to Emerging Technologies. *Rev. Aquac.* **2022**, *14*, 1813–1829. [\[CrossRef\]](#) [\[PubMed\]](#)
94. Aly, S.M.; Fathi, M. Advancing Aquaculture Biosecurity: A Scientometric Analysis and Future Outlook for Disease Prevention and Environmental Sustainability. *Aquac. Int.* **2024**, *32*, 8763–8789. [\[CrossRef\]](#)
95. Cruz, R.C.; Reis Costa, P.; Vinga, S.; Krippahl, L.; Lopes, M.B. A Review of Recent Machine Learning Advances for Forecasting Harmful Algal Blooms and Shellfish Contamination. *J. Mar. Sci. Eng.* **2021**, *9*, 283. [\[CrossRef\]](#)
96. Karras, A.; Karras, C.; Sioutas, S.; Makris, C.; Katselis, G.; Hatzilygeroudis, I.; Theodorou, J.A.; Tsoilis, D. An Integrated GIS-Based Reinforcement Learning Approach for Efficient Prediction of Disease Transmission in Aquaculture. *Information* **2023**, *14*, 583. [\[CrossRef\]](#)
97. Ratan, R.; Ashwini, M.; Nagarajan, V. Artificial Intelligence in Aquaculture: Advancing Monitoring and Sustainability via Remote Sensing. In *Inland Aquaculture Sustainability and Effective Water Management Strategies: Optimizing Resources for Environmental Harmony*; Springer: Berlin/Heidelberg, Germany, 2025; pp. 69–85.
98. Santos, L.; Ramos, F. Antimicrobial Resistance in Aquaculture: Current Knowledge and Alternatives to Tackle the Problem. *Int. J. Antimicrob. Agents* **2018**, *52*, 135–143. [\[CrossRef\]](#) [\[PubMed\]](#)

99. Cabello, F.C. Heavy Use of Prophylactic Antibiotics in Aquaculture: A Growing Problem for Human and Animal Health and for the Environment. *Environ. Microbiol.* **2006**, *8*, 1137–1144. [[CrossRef](#)]
100. Pruden, A.; Larsson, D.J.; Amézquita, A.; Collignon, P.; Brandt, K.K.; Graham, D.W.; Lazorchak, J.M.; Suzuki, S.; Silley, P.; Snape, J.R. Management Options for Reducing the Release of Antibiotics and Antibiotic Resistance Genes to the Environment. *Environ. Health Perspect.* **2013**, *121*, 878–885. [[CrossRef](#)]
101. Cabello, F.C.; Godfrey, H.P.; Tomova, A.; Ivanova, L.; Dölz, H.; Millanao, A.; Buschmann, A.H. Antimicrobial Use in Aquaculture Re-examined: Its Relevance to Antimicrobial Resistance and to Animal and Human Health. *Environ. Microbiol.* **2013**, *15*, 1917–1942. [[CrossRef](#)]
102. Sommerset, I.; Krossøy, B.; Biering, E.; Frost, P. Vaccines for Fish in Aquaculture. *Expert Rev. Vaccines* **2005**, *4*, 89–101. [[CrossRef](#)]
103. Subasinghe, R. Disease Control in Aquaculture and the Responsible Use of Veterinary Drugs and Vaccines: The Issues, Prospects and Challenges. *Options Méditerranéennes* **2009**, *86*, 5e11.
104. Kumar, A.; Middha, S.K.; Menon, S.V.; Paital, B.; Gokarn, S.; Nelli, M.; Rajanikanth, R.B.; Chandra, H.M.; Mugunthan, S.P.; Kantwa, S.M. Current Challenges of Vaccination in Fish Health Management. *Animals* **2024**, *14*, 2692. [[CrossRef](#)]
105. de Andrade Belo, M.A.; Charlie-Silva, I. Teleost Fish as an Experimental Model for Vaccine Development. In *Vaccine Design: Methods and Protocols, Vaccines for Veterinary Diseases*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 2, pp. 175–194.
106. Mondal, H.; Thomas, J. A Review on the Recent Advances and Application of Vaccines against Fish Pathogens in Aquaculture. *Aquac. Int.* **2022**, *30*, 1971–2000. [[CrossRef](#)] [[PubMed](#)]
107. Dadar, M.; Dhama, K.; Vakharia, V.N.; Hoseinifar, S.H.; Karthik, K.; Tiwari, R.; Khandia, R.; Munjal, A.; Salgado-Miranda, C.; Joshi, S.K. Advances in Aquaculture Vaccines against Fish Pathogens: Global Status and Current Trends. *Rev. Fish. Sci. Aquac.* **2017**, *25*, 184–217. [[CrossRef](#)]
108. Adams, A. Progress, Challenges and Opportunities in Fish Vaccine Development. *Fish Shellfish. Immunol.* **2019**, *90*, 210–214. [[CrossRef](#)]
109. Plant, K.P.; LaPatra, S.E. Advances in Fish Vaccine Delivery. *Dev. Comp. Immunol.* **2011**, *35*, 1256–1262. [[CrossRef](#)] [[PubMed](#)]
110. Kumar, G.; Kocour, M. Applications of Next-Generation Sequencing in Fisheries Research: A Review. *Fish. Res.* **2017**, *186*, 11–22. [[CrossRef](#)]
111. Midtlyng, P.J.; Reitan, L.J.; Speilberg, L. Experimental Studies on the Efficacy and Side-Effects of Intraperitoneal Vaccination of Atlantic Salmon (*Salmo salar* L.) against Furunculosis. *Fish Shellfish. Immunol.* **1996**, *6*, 335–350. [[CrossRef](#)]
112. Rathor, G.S.; Swain, B. Advancements in Fish Vaccination: Current Innovations and Future Horizons in Aquaculture Health Management. *Appl. Sci.* **2024**, *14*, 5672. [[CrossRef](#)]
113. Pu, H.; Li, X.; Du, Q.; Cui, H.; Xu, Y. Research Progress in the Application of Chinese Herbal Medicines in Aquaculture: A Review. *Engineering* **2017**, *3*, 731–737. [[CrossRef](#)]
114. Zhu, F. A Review on the Application of Herbal Medicines in the Disease Control of Aquatic Animals. *Aquaculture* **2020**, *526*, 735422. [[CrossRef](#)]
115. Van Hai, N. The Use of Medicinal Plants as Immunostimulants in Aquaculture: A Review. *Aquaculture* **2015**, *446*, 88–96. [[CrossRef](#)]
116. Citarasu, T. Herbal Biomedicines: A New Opportunity for Aquaculture Industry. *Aquac. Int.* **2010**, *18*, 403–414. [[CrossRef](#)]
117. Gatesoupe, F.J. The Use of Probiotics in Aquaculture. *Aquaculture* **1999**, *180*, 147–165. [[CrossRef](#)]
118. Hai, N.V. The Use of Probiotics in Aquaculture. *J. Appl. Microbiol.* **2015**, *119*, 917–935. [[CrossRef](#)]
119. Ringø, E.; Olsen, R.E.; Gifstad, T.; Dalmo, R.A.; Amlund, H.; Hemre, G.-I.; Bakke, A.M. Prebiotics in Aquaculture: A Review. *Aquac. Nutr.* **2010**, *16*, 117–136. [[CrossRef](#)]
120. Carbone, D.; Faggio, C. Importance of Prebiotics in Aquaculture as Immunostimulants. Effects on Immune System of *Sparus aurata* and *Dicentrarchus labrax*. *Fish Shellfish. Immunol.* **2016**, *54*, 172–178. [[CrossRef](#)] [[PubMed](#)]
121. Wee, W.; Hamid, N.K.A.; Mat, K.; Khalif, R.I.A.R.; Rusli, N.D.; Rahman, M.M.; Kabir, M.A.; Wei, L.S. The Effects of Mixed Prebiotics in Aquaculture: A Review. *Aquac. Fish.* **2024**, *9*, 28–34. [[CrossRef](#)]
122. Boyd, C.E.; Schmittou, H.R. Achievement of Sustainable Aquaculture through Environmental Management. *Aquac. Econ. Manag.* **1999**, *3*, 59–69. [[CrossRef](#)]
123. Martins, C.I.M.; Eding, E.H.; Verdegem, M.C.; Heinsbroek, L.T.; Schneider, O.; Blancheton, J.-P.; d’Orbcastel, E.R.; Verreth, J.A.J. New Developments in Recirculating Aquaculture Systems in Europe: A Perspective on Environmental Sustainability. *Aquac. Eng.* **2010**, *43*, 83–93. [[CrossRef](#)]
124. Henriksson, P.J.; Dickson, M.; Allah, A.N.; Al-Kenawy, D.; Phillips, M. Benchmarking the Environmental Performance of Best Management Practice and Genetic Improvements in Egyptian Aquaculture Using Life Cycle Assessment. *Aquaculture* **2017**, *468*, 53–59. [[CrossRef](#)]
125. Brander, K.M. Global Fish Production and Climate Change. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19709–19714. [[CrossRef](#)]
126. De Silva, S.S.; Soto, D. Climate Change and Aquaculture: Potential Impacts, Adaptation and Mitigation. In *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*; FAO Fisheries and Aquaculture Technical Paper; FAO: Rome, Italy, 2009; Volume 530, pp. 151–212.

127. Boonyawiwat, V.; Patanasatienkul, T.; Kasornchandra, J.; Poolkhet, C.; Yaemkasem, S.; Hammell, L.; Davidson, J. Impact of Farm Management on Expression of Early Mortality Syndrome/Acute Hepatopancreatic Necrosis Disease (EMS/AHPND) on Penaeid Shrimp Farms in Thailand. *J. Fish Dis.* **2017**, *40*, 649–659. [[CrossRef](#)]
128. Abolofia, J.; Asche, F.; Wilen, J.E. The Cost of Lice: Quantifying the Impacts of Parasitic Sea Lice on Farmed Salmon. *Mar. Resour. Econ.* **2017**, *32*, 329–349. [[CrossRef](#)]
129. Pahlow, M.; Van Oel, P.R.; Mekonnen, M.M.; Hoekstra, A.Y. Increasing Pressure on Freshwater Resources Due to Terrestrial Feed Ingredients for Aquaculture Production. *Sci. Total Environ.* **2015**, *536*, 847–857. [[CrossRef](#)] [[PubMed](#)]
130. Waite, R.; Beveridge, M.; Brummett, R.; Castine, S.; Chaipayannakarn, N.; Kaushik, S.; Mungkung, R.; Nawapakpilai, S.; Phillips, M. *Improving Productivity and Environmental Performance of Aquaculture*; WorldFish: Penang, Malaysia, 2014.
131. Primavera, J.H. Overcoming the Impacts of Aquaculture on the Coastal Zone. *Ocean. Coast. Manag.* **2006**, *49*, 531–545. [[CrossRef](#)]
132. Song, Y.; Zhang, W. Balancing Growth and Sustainability in China's Carp Aquaculture: Practices, Policies, and Sustainability Pathways. *Sustainability* **2025**, *17*, 5593. [[CrossRef](#)]
133. Pomeroy, R.S.; Andrew, N. *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World*; CABI: Carson, CA, USA, 2011; ISBN 1-84593-608-6.
134. Perumal, S.; Thirunavukkarasu, A.R.; Pachiappan, P. *Advances in Marine and Brackishwater Aquaculture*; Springer: Berlin/Heidelberg, Germany, 2015.
135. Huntingford, F.A.; Adams, C.; Braithwaite, V.A.; Kadri, S.; Pottinger, T.G.; Sandøe, P.; Turnbull, J.F. Current Issues in Fish Welfare. *J. Fish Biol.* **2006**, *68*, 332–372. [[CrossRef](#)]
136. Stentiford, G.D.; Longshaw, M.; Lyons, B.P.; Jones, G.; Green, M.; Feist, S.W. Histopathological Biomarkers in Estuarine Fish Species for the Assessment of Biological Effects of Contaminants. *Mar. Environ. Res.* **2003**, *55*, 137–159. [[CrossRef](#)]
137. Abdelsalam, M.; Elgendy, M.Y.; Elfadadny, M.R.; Ali, S.S.; Sherif, A.H.; Abolghait, S.K. A Review of Molecular Diagnoses of Bacterial Fish Diseases. *Aquac. Int.* **2023**, *31*, 417–434. [[CrossRef](#)]
138. Huver, J.R.; Koprivnikar, J.; Johnson, P.T.J.; Whyard, S. Development and Application of an eDNA Method to Detect and Quantify a Pathogenic Parasite in Aquatic Ecosystems. *Ecol. Appl.* **2015**, *25*, 991–1002. [[CrossRef](#)]
139. Wittwer, C.; Stoll, S.; Strand, D.; Vrålstad, T.; Nowak, C.; Thines, M. eDNA-Based Crayfish Plague Monitoring Is Superior to Conventional Trap-Based Assessments in Year-Round Detection Probability. *Hydrobiologia* **2018**, *807*, 87–97. [[CrossRef](#)]
140. Aftab, K.; Tschirren, L.; Pasini, B.; Zeller, P.; Khan, B.; Fraz, M.M. Intelligent Fisheries: Cognitive Solutions for Improving Aquaculture Commercial Efficiency through Enhanced Biomass Estimation and Early Disease Detection. *Cogn. Comput.* **2024**, *16*, 2241–2263. [[CrossRef](#)]
141. Arthur, J.; Bondad-Reantaso, M.; Campbell, M.; Hewitt, C.; Phillips, M.; Subasinghe, R. *Understanding and Applying Risk Analysis in Aquaculture: A Manual for Decision-Makers*; CQUniversity: Rockhampton, Australia, 2009; ISBN 92-5-106414-8.
142. Action, S.I. World Fisheries and Aquaculture. *Food Agric. Organ.* **2020**, *2020*, 1–244.
143. Sedyaw, P.; Bhatkar, V.R. A Review on Application of Aquaculture Drugs for Sustainable Aquaculture. *J. Dev. Res.* **2024**, *14*, 66685–66690.
144. Miranda, C.D.; Godoy, F.A.; Lee, M.R. Current Status of the Use of Antibiotics and the Antimicrobial Resistance in the Chilean Salmon Farms. *Front. Microbiol.* **2018**, *9*, 1284. [[CrossRef](#)]
145. Caputo, A.; Bondad-Reantaso, M.G.; Karunasagar, I.; Hao, B.; Gaunt, P.; Verner-Jeffreys, D.; Fridman, S.; Dorado-Garcia, A. Antimicrobial Resistance in Aquaculture: A Global Analysis of Literature and National Action Plans. *Rev. Aquac.* **2023**, *15*, 568–578. [[CrossRef](#)]
146. Watts, J.E.; Schreier, H.J.; Lanska, L.; Hale, M.S. The Rising Tide of Antimicrobial Resistance in Aquaculture: Sources, Sinks and Solutions. *Mar. Drugs* **2017**, *15*, 158. [[CrossRef](#)]
147. Stentiford, G.D.; Bateman, I.J.; Hinchliffe, S.J.; Bass, D.; Hartnell, R.; Santos, E.M.; Devlin, M.J.; Feist, S.W.; Taylor, N.G.H.; Verner-Jeffreys, D.W. Sustainable Aquaculture through the One Health Lens. *Nat. Food* **2020**, *1*, 468–474. [[CrossRef](#)] [[PubMed](#)]
148. EFSA Panel on Biological Hazards (BIOHAZ); Koutsoumanis, K.; Allende, A.; Álvarez-Ordóñez, A.; Bolton, D.; Bover-Cid, S.; Chemaly, M.; Davies, R.; De Cesare, A.; Herman, L. Role Played by the Environment in the Emergence and Spread of Antimicrobial Resistance (AMR) through the Food Chain. *EFSA J.* **2021**, *19*, e06651. [[CrossRef](#)]
149. Chen, H.; Liu, S.; Xu, X.-R.; Liu, S.-S.; Zhou, G.-J.; Sun, K.-F.; Zhao, J.-L.; Ying, G.-G. Antibiotics in Typical Marine Aquaculture Farms Surrounding Hailing Island, South China: Occurrence, Bioaccumulation and Human Dietary Exposure. *Mar. Pollut. Bull.* **2015**, *90*, 181–187. [[CrossRef](#)] [[PubMed](#)]
150. Yang, J.; Wang, C.; Shu, C.; Liu, L.; Geng, J.; Hu, S.; Feng, J. Marine Sediment Bacteria Harbor Antibiotic Resistance Genes Highly Similar to Those Found in Human Pathogens. *Microb. Ecol.* **2013**, *65*, 975–981. [[CrossRef](#)]
151. Kümmerer, K. Antibiotics in the Aquatic Environment—a Review—Part I. *Chemosphere* **2009**, *75*, 417–434. [[CrossRef](#)] [[PubMed](#)]
152. Gauthier, D.T. Bacterial Zoonoses of Fishes: A Review and Appraisal of Evidence for Linkages between Fish and Human Infections. *Vet. J.* **2015**, *203*, 27–35. [[CrossRef](#)] [[PubMed](#)]

153. Sousa, M.; Torres, C.; Barros, J.; Somalo, S.; Igrejas, G.; Poeta, P. Gilthead Seabream (*Sparus aurata*) as Carriers of SHV-12 and TEM-52 Extended-Spectrum Beta-Lactamases-Containing Escherichia Coli Isolates. *Foodborne Pathog. Dis.* **2011**, *8*, 1139–1141. [CrossRef]
154. Mog, M.; Ngasotter, S.; Tesia, S.; Waikhom, D.; Panda, P.; Sharma, S.; Varshney, S. Problems of Antibiotic Resistance Associated with Oxytetracycline Use in Aquaculture: A Review. *J. Entomol. Zool. Stud.* **2020**, *8*, 1075–1082.
155. Le Curieux, F.; Gohlke, J.M.; Pronk, A.; Andersen, W.C.; Chen, G.; Fang, J.-L.; Mitrowska, K.; Sanders, P.J.; Sun, M.; Umbuzeiro, G.A. Carcinogenicity of Gentian Violet, Leucogentian Violet, Malachite Green, Leucomalachite Green, and CI Direct Blue 218. *Lancet Oncol.* **2021**, *22*, 585–586. [CrossRef]
156. Gharavi-Nakhjavani, M.S.; Niazi, A.; Hosseini, H.; Aminzare, M.; Dizaji, R.; Tajdar-Oranj, B.; Mirza Alizadeh, A. Malachite Green and Leucomalachite Green in Fish: A Global Systematic Review and Meta-Analysis. *Environ. Sci. Pollut. Res.* **2023**, *30*, 48911–48927. [CrossRef]
157. O'Neill, J. Antimicrobials in Agriculture and the Environment: Reducing Unnecessary Use and Waste. In *The Review on Antimicrobial Resistance*; HM Government: London, UK, 2015.
158. Silva, Y.J.; Costa, L.; Pereira, C.; Cunha, Â.; Calado, R.; Gomes, N.C.; Almeida, A. Influence of Environmental Variables in the Efficiency of Phage Therapy in Aquaculture. *Microb. Biotechnol.* **2014**, *7*, 401–413. [CrossRef]
159. Zhao, J.; Chen, M.; Quan, C.S.; Fan, S.D. Mechanisms of Quorum Sensing and Strategies for Quorum Sensing Disruption in Aquaculture Pathogens. *J. Fish Dis.* **2015**, *38*, 771–786. [CrossRef]
160. Li, S.; Zhang, S.; Ye, C.; Lin, W.; Zhang, M.; Chen, L.; Li, J.; Yu, X. Biofilm Processes in Treating Mariculture Wastewater May Be a Reservoir of Antibiotic Resistance Genes. *Mar. Pollut. Bull.* **2017**, *118*, 289–296. [CrossRef]
161. Jefferson, K.K. What Drives Bacteria to Produce a Biofilm? *FEMS Microbiol. Lett.* **2004**, *236*, 163–173. [CrossRef]
162. Summerfelt, S.T. Ozonation and UV Irradiation—An Introduction and Examples of Current Applications. *Aquac. Eng.* **2003**, *28*, 21–36. [CrossRef]
163. Powell, A.; Scolding, J.W. Direct Application of Ozone in Aquaculture Systems. *Rev. Aquac.* **2018**, *10*, 424–438. [CrossRef]
164. Chuah, L.-O.; Effarizah, M.E.; Goni, A.M.; Rusul, G. Antibiotic Application and Emergence of Multiple Antibiotic Resistance (MAR) in Global Catfish Aquaculture. *Curr. Environ. Health Rep.* **2016**, *3*, 118–127. [CrossRef]
165. Tollefson, L.; Miller, M.A. Antibiotic Use in Food Animals: Controlling the Human Health Impact. *J. AOAC Int.* **2000**, *83*, 245–254. [CrossRef]
166. Schar, D.; Klein, E.Y.; Laxminarayan, R.; Gilbert, M.; Van Boeckel, T.P. Global Trends in Antimicrobial Use in Aquaculture. *Sci. Rep.* **2020**, *10*, 21878. [CrossRef] [PubMed]
167. Baynes, R.E.; Dedonder, K.; Kissell, L.; Mzyk, D.; Marmulak, T.; Smith, G.; Tell, L.; Gehring, R.; Davis, J.; Riviere, J.E. Health Concerns and Management of Select Veterinary Drug Residues. *Food Chem. Toxicol.* **2016**, *88*, 112–122. [CrossRef] [PubMed]
168. Canton, L.; Lanusse, C.; Moreno, L. Rational Pharmacotherapy in Infectious Diseases: Issues Related to Drug Residues in Edible Animal Tissues. *Animals* **2021**, *11*, 2878. [CrossRef] [PubMed]
169. Lee, M.H.; Lee, H.J.; Ryu, P.D. Public Health Risks: Chemical and Antibiotic Residues-Review. *Asian-Australas. J. Anim. Sci.* **2001**, *14*, 402–413. [CrossRef]
170. FDA. Approved Aquaculture Drugs. Available online: <https://www.fda.gov/animal-veterinary/aquaculture/approved-aquaculture-drugs> (accessed on 21 September 2025).
171. Faria, P.B.; Erasmus, S.W.; Bruhn, F.R.; van Ruth, S.M. An Account of the Occurrence of Residues from Veterinary Drugs and Contaminants in Animal-Derived Products: A Case Study on Brazilian Supply Chains. *Food Addit. Contam. Part A* **2024**, *41*, 365–384. [CrossRef]
172. Danaher, M.; Prendergast, D.M. A European Food Safety Perspective on Residues of Veterinary Drugs and Growth-Promoting Agents. In *Pathogens and Toxins in Foods: Challenges and Interventions*; Wiley: Hoboken, NJ, USA, 2009; pp. 326–342.
173. Padros, F.; Gourzioti, E.; Fabris, A.; Figenschou, A.; Manfrin, A.; Metselaar, M.; Palić, D.; Vesanto, S. Relevance of Pharmacovigilance in Aquatic Animal Medicine. A Perspective from Aquaculture Health Experts Attending a Focus Group Meeting at the EMA. *Bull. Eur. Assoc. Fish Pathol.* **2024**, *44*, 1–10. [CrossRef]
174. De la Casa-Resino, I.; Empl, M.T.; Villa, S.; Kolar, B.; Fabrega, J.; Lillicrap, A.D.; Karamanlis, X.N.; Carapeto-García, R. Environmental Risk Assessment of Veterinary Medicinal Products Intended for Use in Aquaculture in Europe: The Need for Developing a Harmonised Approach. *Environ. Sci. Eur.* **2021**, *33*, 84. [CrossRef]
175. Gravningen, K.; Sorum, H.; Horsberg, T.E. The Future of Therapeutic Agents in Aquaculture. *Rev. Sci. Tech. (Int. Off. Epizoot.)* **2019**, *38*, 641–651. [CrossRef]
176. Rigos, G.; Kogiannou, D.; Padrós, F.; Cristofol, C.; Florio, D.; Fioravanti, M.; Zarza, C. Best Therapeutic Practices for the Use of Antibacterial Agents in Finfish Aquaculture: A Particular View on European Seabass (*Dicentrarchus labrax*) and Gilthead Seabream (*Sparus aurata*) in Mediterranean Aquaculture. *Rev. Aquac.* **2021**, *13*, 1285–1323. [CrossRef]

177. Rico, A.; Vighi, M.; Van den Brink, P.J.; ter Horst, M.; Macken, A.; Lillicrap, A.; Falconer, L.; Telfer, T.C. Use of Models for the Environmental Risk Assessment of Veterinary Medicines in European Aquaculture: Current Situation and Future Perspectives. *Rev. Aquac.* **2019**, *11*, 969–988. [\[CrossRef\]](#)
178. Brooks, B.W.; Ankley, G.T.; Hobson, J.F.; Lazorchak, J.M.; Meyerhoff, R.D.; Solomon, K.R. Assessing the Aquatic Hazards of Veterinary Medicines. In *Effects of Veterinary Medicines in the Environment*; CRC Press: Boca Raton, FL, USA, 2008; pp. 97–128.
179. Olsen, M.; Petersen, K.; Lehoux, A.P.; Leppänen, M.; Schaanning, M.; Snowball, I.; Øxnevad, S.; Lund, E. *Contaminated Sediments: Review of Solutions for Protecting Aquatic Environments*; Nordic Council of Ministers: Copenhagen, Denmark, 2019.
180. Abdelkarim, E.A.; Elsamahy, T.; El Bayomi, R.M.; Hussein, M.A.; Darwish, I.A.; El-tahlawy, A.S.; Alahmad, W.; Darling, R.J.; Hafez, A.E.-S.E.; Sobhi, M. Nanoparticle-Driven Aquaculture: Transforming Disease Management and Boosting Sustainable Fish Farming Practices. *Aquac. Int.* **2025**, *33*, 288. [\[CrossRef\]](#)
181. Lall, S.P.; Kaushik, S.J. Nutrition and Metabolism of Minerals in Fish. *Animals* **2021**, *11*, 2711. [\[CrossRef\]](#) [\[PubMed\]](#)
182. Tacon, A.G.; Metian, M. Feed Matters: Satisfying the Feed Demand of Aquaculture. *Rev. Fish. Sci. Aquac.* **2015**, *23*, 1–10. [\[CrossRef\]](#)
183. Glencross, B.D.; Booth, M.; Allan, G.L. A Feed Is Only as Good as Its Ingredients—a Review of Ingredient Evaluation Strategies for Aquaculture Feeds. *Aquac. Nutr.* **2007**, *13*, 17–34. [\[CrossRef\]](#)
184. Hardy, R.W. Utilization of Plant Proteins in Fish Diets: Effects of Global Demand and Supplies of Fishmeal. *Aquac. Res.* **2010**, *41*, 770–776. [\[CrossRef\]](#)
185. Gatlin III, D.M.; Barrows, F.T.; Brown, P.; Dabrowski, K.; Gaylord, T.G.; Hardy, R.W.; Herman, E.; Hu, G.; Krogdahl, Å.; Nelson, R. Expanding the Utilization of Sustainable Plant Products in Aquafeeds: A Review. *Aquac. Res.* **2007**, *38*, 551–579. [\[CrossRef\]](#)
186. Kumar, V.; Makkar, H.P.S.; Becker, K. Nutritional, Physiological and Haematological Responses in Rainbow Trout (*Oncorhynchus mykiss*) Juveniles Fed Detoxified Jatropha Curcas Kernel Meal. *Aquac. Nutr.* **2011**, *17*, 451–467. [\[CrossRef\]](#)
187. Prabu, E.; Felix, S.; Felix, N.; Ahilan, B.; Ruby, P. An Overview on Significance of Fish Nutrition in Aquaculture Industry. *Int. J. Fish. Aquat. Stud.* **2017**, *5*, 349–355.
188. Craig, S.R.; Helfrich, L.A.; Kuhn, D.; Schwarz, M.H. *Understanding Fish Nutrition, Feeds, and Feeding*; Virginia Cooperative Extension: Petersburg, VA, USA, 2017.
189. Bell, J.G.; Koppe, W. Lipids in Aquafeeds. In *Fish Oil Replacement and Alternative Lipid Sources in Aquaculture Feeds*; CRC Press: Boca Raton, FL, USA, 2010; Volume 1, pp. 21–59.
190. Radhakrishnan, D.K.; AkbarAli, I.; Velayudhannair, K.; Kari, Z.A.; Liew, H.J. Exploring the Role of Plant Oils in Aquaculture Practices: An Overview. *Aquac. Int.* **2024**, *32*, 7719–7745. [\[CrossRef\]](#)
191. Alhazaa, R.; Nichols, P.D.; Carter, C.G. Sustainable Alternatives to Dietary Fish Oil in Tropical Fish Aquaculture. *Rev. Aquac.* **2019**, *11*, 1195–1218. [\[CrossRef\]](#)
192. Hemre, G.-I.; Mommsen, T.P.; Krogdahl, Å. Carbohydrates in Fish Nutrition: Effects on Growth, Glucose Metabolism and Hepatic Enzymes. *Aquac. Nutr.* **2002**, *8*, 175–194. [\[CrossRef\]](#)
193. Stone, D.A. Dietary Carbohydrate Utilization by Fish. *Rev. Fish. Sci.* **2003**, *11*, 337–369. [\[CrossRef\]](#)
194. Oliva-Teles, A. Nutrition and Health of Aquaculture Fish. *J. Fish Dis.* **2012**, *35*, 83–108. [\[CrossRef\]](#)
195. Khalili Tilami, S.; Sampels, S. Nutritional Value of Fish: Lipids, Proteins, Vitamins, and Minerals. *Rev. Fish. Sci. Aquac.* **2018**, *26*, 243–253. [\[CrossRef\]](#)
196. Chanda, S.; Paul, B.N.; Ghosh, K.; Giri, S.S. Dietary Essentiality of Trace Minerals in Aquaculture-A Review. *Agric. Rev.* **2015**, *36*, 100–112. [\[CrossRef\]](#)
197. Antony Jesu Prabhu, P.; Schrama, J.W.; Kaushik, S.J. Mineral Requirements of Fish: A Systematic Review. *Rev. Aquac.* **2016**, *8*, 172–219. [\[CrossRef\]](#)
198. Panteli, N.; Kousoulaki, K.; Antonopoulou, E.; Carter, C.G.; Nengas, I.; Henry, M.; Karapanagiotidis, I.T.; Mente, E. Which Novel Ingredient Should Be Considered the “Holy Grail” for Sustainable Production of Finfish Aquafeeds? *Rev. Aquac.* **2025**, *17*, e12969. [\[CrossRef\]](#)
199. Meena, D.K.; Das, P.; Kumar, S.; Mandal, S.C.; Prusty, A.K.; Singh, S.K.; Akhtar, M.S.; Behera, B.K.; Kumar, K.; Pal, A.K. Beta-Glucan: An Ideal Immunostimulant in Aquaculture (a Review). *Fish Physiol. Biochem.* **2013**, *39*, 431–457. [\[CrossRef\]](#)
200. Dawood, M.A.; Koshio, S.; Esteban, M.Á. Beneficial Roles of Feed Additives as Immunostimulants in Aquaculture: A Review. *Rev. Aquac.* **2018**, *10*, 950–974. [\[CrossRef\]](#)
201. Pigott, G.M.; Tucker, B. *Seafood: Effects of Technology on Nutrition*; CRC press: Boca Raton, FL, USA, 2017; ISBN 0-203-74011-4.
202. Sugiura, S.H.; Marchant, D.D.; Kelsey, K.; Wiggins, T.; Ferraris, R.P. Effluent Profile of Commercially Used Low-Phosphorus Fish Feeds. *Environ. Pollut.* **2006**, *140*, 95–101. [\[CrossRef\]](#)
203. Aksnes, A.; Hjertnes, T.; Opstvedt, J. Comparison of Two Assay Methods for Determination of Nutrient and Energy Digestibility in Fish. *Aquaculture* **1996**, *140*, 343–359. [\[CrossRef\]](#)
204. Kan, C.A.; Meijer, G.A.L. The Risk of Contamination of Food with Toxic Substances Present in Animal Feed. *Anim. Feed. Sci. Technol.* **2007**, *133*, 84–108. [\[CrossRef\]](#)

205. Lunestad, B.T.; Nesse, L.; Lassen, J.; Svihus, B.; Nesbakken, T.; Fossum, K.; Rosnes, J.T.; Kruse, H.; Yazdankhah, S. *Salmonella* in Fish Feed; Occurrence and Implications for Fish and Human Health in Norway. *Aquaculture* **2007**, *265*, 1–8. [\[CrossRef\]](#)
206. Santacroce, M.P.; Conversano, M.C.; Casalino, E.; Lai, O.; Zizzadoro, C.; Centoducati, G.; Crescenzo, G. Aflatoxins in Aquatic Species: Metabolism, Toxicity and Perspectives. *Rev. Fish Biol. Fish.* **2008**, *18*, 99–130. [\[CrossRef\]](#)
207. Stolker, A.A.M.; Zuidema, T.; Nielen, M.W.F. Residue Analysis of Veterinary Drugs and Growth-Promoting Agents. *TrAC Trends Anal. Chem.* **2007**, *26*, 967–979. [\[CrossRef\]](#)
208. Maule, A.G.; Gannam, A.L.; Davis, J.W. Chemical Contaminants in Fish Feeds Used in Federal Salmonid Hatcheries in the USA. *Chemosphere* **2007**, *67*, 1308–1315. [\[CrossRef\]](#)
209. Tacon, A.G.; Metian, M. Aquaculture Feed and Food Safety: The Role of the Food and Agriculture Organization and the Codex Alimentarius. *Ann. New York Acad. Sci.* **2008**, *1140*, 50–59. [\[CrossRef\]](#) [\[PubMed\]](#)
210. Food and Agriculture Organization (FAO). *Animal Feeding and Food Safety*; Food and Nutrition Paper 69; FAO: Rome, Italy, 1998. Available online: <http://www.fao.org/docrep/w8901e/w8901e00.htm> (accessed on 21 September 2025).
211. Tschirner, M.; Kloas, W. Increasing the Sustainability of Aquaculture Systems: Insects as Alternative Protein Source for Fish Diets. *GAIA-Ecol. Perspect. Sci. Soc.* **2017**, *26*, 332–340. [\[CrossRef\]](#)
212. Gómez, B.; Munekata, P.E.; Zhu, Z.; Barba, F.J.; Toldrá, F.; Putnik, P.; Kovačević, D.B.; Lorenzo, J.M. Challenges and Opportunities Regarding the Use of Alternative Protein Sources: Aquaculture and Insects. *Adv. Food Nutr. Res.* **2019**, *89*, 259–295. [\[PubMed\]](#)
213. Auzins, A.; Leimane, I.; Reissaar, R.; Brobak, J.; Sakelaite, I.; Grivins, M.; Zihare, L. Assessing the Socio-Economic Benefits and Costs of Insect Meal as a Fishmeal Substitute in Livestock and Aquaculture. *Animals* **2024**, *14*, 1461. [\[CrossRef\]](#) [\[PubMed\]](#)
214. Shah, M.R.; Lutz, G.A.; Alam, A.; Sarker, P.; Kabir Chowdhury, M.A.; Parsaeimehr, A.; Liang, Y.; Daroch, M. Microalgae in Aquafeeds for a Sustainable Aquaculture Industry. *J. Appl. Phycol.* **2018**, *30*, 197–213. [\[CrossRef\]](#)
215. Hussain, A.; Khan, G.M.; Khan, N.R.; Khan, A.; Rehman, S.U.; Asif, H.M.; Akram, M.; Ali, Y. Transdermal Diclofenac Potassium Gels: Natural Penetration Enhancers, Can Be Effective? *Lat. Am. J. Pharm.* **2015**, *34*, 1022–1029.
216. Chamodi, K.K.D.; Vu, N.T.; Domingos, J.A.; Loh, J.-Y. Cellular Solutions: Evaluating Single-Cell Proteins as Sustainable Feed Alternatives in Aquaculture. *Biology* **2025**, *14*, 764. [\[CrossRef\]](#)
217. Malcorps, W.; Kok, B.; van 't Land, M.; Fritz, M.; van Doren, D.; Servin, K.; Van der Heijden, P.; Palmer, R.; Auchterlonie, N.A.; Rietkerk, M. The Sustainability Conundrum of Fishmeal Substitution by Plant Ingredients in Shrimp Feeds. *Sustainability* **2019**, *11*, 1212. [\[CrossRef\]](#)
218. Kader, M.A.; Bulbul, M.; Koshio, S.; Ishikawa, M.; Yokoyama, S.; Nguyen, B.T.; Komilus, C.F. Effect of Complete Replacement of Fishmeal by Dehulled Soybean Meal with Crude Attractants Supplementation in Diets for Red Sea Bream, *Pagrus Major*. *Aquaculture* **2012**, *350*, 109–116. [\[CrossRef\]](#)
219. He, M.; Li, X.; Poolsawat, L.; Guo, Z.; Yao, W.; Zhang, C.; Leng, X. Effects of Fish Meal Replaced by Fermented Soybean Meal on Growth Performance, Intestinal Histology and Microbiota of Largemouth Bass (*Micropterus salmoides*). *Aquac. Nutr.* **2020**, *26*, 1058–1071. [\[CrossRef\]](#)
220. Daniel, N. A Review on Replacing Fish Meal in Aqua Feeds Using Plant Protein Sources. *Int. J. Fish. Aquat. Stud.* **2018**, *6*, 164–179.
221. Hua, K.; Cobcroft, J.M.; Cole, A.; Condon, K.; Jerry, D.R.; Mangott, A.; Praeger, C.; Vucko, M.J.; Zeng, C.; Zenger, K. The Future of Aquatic Protein: Implications for Protein Sources in Aquaculture Diets. *One Earth* **2019**, *1*, 316–329. [\[CrossRef\]](#)
222. Kim, S.W.; Less, J.F.; Wang, L.; Yan, T.; Kiron, V.; Kaushik, S.J.; Lei, X.G. Meeting Global Feed Protein Demand: Challenge, Opportunity, and Strategy. *Annu. Rev. Anim. Biosci.* **2019**, *7*, 221–243. [\[CrossRef\]](#)
223. Kause, A.; Kiessling, A.; Martin, S.A.; Houlihan, D.; Ruohonen, K. Genetic Improvement of Feed Conversion Ratio via Indirect Selection against Lipid Deposition in Farmed Rainbow Trout (*Oncorhynchus mykiss* Walbaum). *Br. J. Nutr.* **2016**, *116*, 1656–1665. [\[CrossRef\]](#)
224. Santos, A.I.; Nguyen, N.H.; Ponzoni, R.W.; Yee, H.Y.; Hamzah, A.; Ribeiro, R.P. Growth and Survival Rate of Three Genetic Groups Fed 28% and 34% Protein Diets. *Aquac. Res.* **2014**, *45*, 353–361. [\[CrossRef\]](#)
225. Glencross, B.; Tabrett, S.; Irvin, S.; Wade, N.; Anderson, M.; Blyth, D.; Smith, D.; Coman, G.; Preston, N. An Analysis of the Effect of Diet and Genotype on Protein and Energy Utilization by the Black Tiger Shrimp, *Penaeus Monodon*—Why Do Genetically Selected Shrimp Grow Faster? *Aquac. Nutr.* **2013**, *19*, 128–138. [\[CrossRef\]](#)
226. Hallstein, E.; Villas-Boas, S.B. Can Household Consumers Save the Wild Fish? Lessons from a Sustainable Seafood Advisory. *J. Environ. Econ. Manag.* **2013**, *66*, 52–71. [\[CrossRef\]](#)
227. Vijayaram, S.; Sun, Y.-Z.; Zuorro, A.; Ghafarifarsani, H.; Van Doan, H.; Hoseinifar, S.H. Bioactive Immunostimulants as Health-Promoting Feed Additives in Aquaculture: A Review. *Fish Shellfish. Immunol.* **2022**, *130*, 294–308. [\[CrossRef\]](#)
228. Yang, K.; Qi, X.; He, M.; Song, K.; Luo, F.; Qu, X.; Wang, G.; Ling, F. Dietary Supplementation of Salidroside Increases Immune Response and Disease Resistance of Crucian Carp (*Carassius auratus*) against *Aeromonas hydrophila*. *Fish Shellfish. Immunol.* **2020**, *106*, 1–7. [\[CrossRef\]](#)

229. Magrone, T.; Fontana, S.; Laforgia, F.; Dragone, T.; Jirillo, E.; Passantino, L. Administration of a Polyphenol-enriched Feed to Farmed Sea Bass (*Dicentrarchus labrax* L.) Modulates Intestinal and Spleen Immune Responses. *Oxidative Med. Cell. Longev.* **2016**, *2016*, 2827567. [\[CrossRef\]](#)
230. Hoseinifar, S.H.; Sun, Y.-Z.; Zhou, Z.; Van Doan, H.; Davies, S.J.; Harikrishnan, R. Boosting Immune Function and Disease Bio-Control through Environment-Friendly and Sustainable Approaches in Finfish Aquaculture: Herbal Therapy Scenarios. *Rev. Fish. Sci. Aquac.* **2020**, *28*, 303–321. [\[CrossRef\]](#)
231. Gurjar, V.K.; Pal, D. Natural Compounds Extracted from Medicinal Plants and Their Immunomodulatory Activities. In *Bioactive Natural Products for Pharmaceutical Applications*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 197–261.
232. Mendoza Rodriguez, M.G.; Pohlenz, C.; Gatlin III, D.M. Supplementation of Organic Acids and Algae Extracts in the Diet of Red Drum *Sciaenops Ocellatus*: Immunological Impacts. *Aquac. Res.* **2017**, *48*, 1778–1786. [\[CrossRef\]](#)
233. Suttili, F.J.; Gatlin III, D.M.; Heinzmann, B.M.; Baldisserotto, B. Plant Essential Oils as Fish Diet Additives: Benefits on Fish Health and Stability in Feed. *Rev. Aquac.* **2018**, *10*, 716–726. [\[CrossRef\]](#)
234. Zhang, R.; Wang, X.W.; Liu, L.L.; Cao, Y.C.; Zhu, H. Dietary Oregano Essential Oil Improved the Immune Response, Activity of Digestive Enzymes, and Intestinal Microbiota of the Koi Carp, *Cyprinus carpio*. *Aquaculture* **2020**, *518*, 734781. [\[CrossRef\]](#)
235. Akter, M.N.; Zahan, K.; Zafar, M.A.; Khatun, N.; Rana, M.S.; Mursalin, M.I. Effects of Dietary Mannan Oligosaccharide on Growth Performance, Feed Utilization, Body Composition and Haematological Parameters in Asian Catfish (*Clarias batrachus*) Juveniles. *Turk. J. Fish. Aquat. Sci.* **2021**, *21*, 559–567. [\[CrossRef\]](#)
236. Sheng, L.; Wang, L. The Microbial Safety of Fish and Fish Products: Recent Advances in Understanding Its Significance, Contamination Sources, and Control Strategies. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 738–786. [\[CrossRef\]](#) [\[PubMed\]](#)
237. Ghaly, A.E.; Dave, D.; Budge, S.; Brooks, M.S. Fish Spoilage Mechanisms and Preservation Techniques. *Am. J. Appl. Sci.* **2010**, *7*, 859. [\[CrossRef\]](#)
238. Luqman, M.; Hassan, H.U.; Ghaffar, R.A.; Bilal, M.; Kanwal, R.; Raza, M.A.; Kabir, M.; Fadladdin, Y.A.J.; Ali, A.; Rafiq, N. Post-Harvest Bacterial Contamination of Fish, Their Assessment and Control Strategies. *Braz. J. Biol.* **2024**, *84*, e282002. [\[CrossRef\]](#) [\[PubMed\]](#)
239. Poli, B.M.; Parisi, G.; Scappini, F.; Zampacavallo, G. Fish Welfare and Quality as Affected by Pre-Slaughter and Slaughter Management. *Aquac. Int.* **2005**, *13*, 29–49. [\[CrossRef\]](#)
240. Peng, L.; Zhang, L.; Xiong, S.; You, J.; Liu, R.; Xu, D.; Huang, Q.; Ma, H.; Yin, T. A Comprehensive Review of the Mechanisms on Fish Stress Affecting Muscle Qualities: Nutrition, Physical Properties, and Flavor. *Compr. Rev. Food Sci. Food Saf.* **2024**, *23*, e13336. [\[CrossRef\]](#)
241. Vijayan, M.M.; Pereira, C.; Grau, E.G.; Iwama, G.K. Metabolic Responses Associated with Confinement Stress in Tilapia: The Role of Cortisol. *Comp. Biochem. Physiol. Part C Pharmacol. Toxicol. Endocrinol.* **1997**, *116*, 89–95. [\[CrossRef\]](#)
242. Bermejo-Poza, R.; De la Fuente, J.; Pérez, C.; de Chavarri, E.G.; Diaz, M.T.; Torrent, F.; Villarroel, M. Determination of Optimal Degree Days of Fasting before Slaughter in Rainbow Trout (*Oncorhynchus mykiss*). *Aquaculture* **2017**, *473*, 272–277. [\[CrossRef\]](#)
243. Ojelade, O.C.; George, F.O.A.; Abdulraheem, I.; Akinde, A.O. Interactions between Pre-Harvest, Post-Harvest Handling and Welfare of Fish for Sustainability in the Aquaculture Sector. In *Emerging Sustainable Aquaculture Innovations in Africa*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 525–541.
244. Pongsetkul, J.; Benjakul, S.; Takeungwongtrakul, S.; Sai-ut, S. Impact of Stocking Density during Live Transportation on Meat Quality of Nile Tilapia (*Oreochromis niloticus*) and Their Changes during Storage. *J. Food Process. Preserv.* **2022**, *46*, e16523. [\[CrossRef\]](#)
245. López-Cánovas, A.E.; Cabas, I.; Ros-Chumillas, M.; Navarro-Segura, L.; López-Gómez, A.; García-Ayala, A. Nanoencapsulated Clove Essential Oil Applied in Low Dose Decreases Stress in Farmed Gilthead Seabream (*Sparus aurata* L.) during Slaughter by Hypothermia in Ice Slurry. *Aquaculture* **2019**, *504*, 437–445. [\[CrossRef\]](#)
246. Authority (EFSA), E.F.S. Food Safety Considerations Concerning the Species-specific Welfare Aspects of the Main Systems of Stunning and Killing of Farmed Fish. *EFSA J.* **2009**, *7*, 1190. [\[CrossRef\]](#)
247. Sundell, E.; Brijs, J.; Gräns, A. The Quest for a Humane Protocol for Stunning and Killing Nile Tilapia (*Oreochromis niloticus*). *Aquaculture* **2024**, *593*, 741317. [\[CrossRef\]](#)
248. Kumar, P.; Abubakar, A.A.; Sazili, A.Q.; Kaka, U.; Goh, Y.-M. Application of Electroencephalography in Preslaughter Management: A Review. *Animals* **2022**, *12*, 2857. [\[CrossRef\]](#)
249. World Organization for Animal Health (OIE). *Welfare Aspects of Stunning and Killing of Farmed Fish for Human Consumption*. *Aquatic Animal Health Code*; World Organization for Animal Health: Paris, France, 2010; pp. 129–133.
250. Terlouw, C.; Bourguet, C.; Deiss, V. Consciousness, Unconsciousness and Death in the Context of Slaughter. Part II. Evaluation Methods. *Meat Sci.* **2016**, *118*, 147–156. [\[CrossRef\]](#) [\[PubMed\]](#)
251. Rucinque, D.S.; Pulecio-Santos, S.L.; Viegas, E.M.M. Impact of Pre-Slaughter Methods on the Overall Quality of Nile Tilapia (*Oreochromis niloticus*). *J. Aquat. Food Prod. Technol.* **2023**, *32*, 447–461. [\[CrossRef\]](#)

252. Robb, D.H.F.; Wotton, S.B.; McKinsty, J.L.; Sørensen, N.K.; Kestin, S.C.; Sørensen, N.K. Commercial Slaughter Methods Used on Atlantic Salmon: Determination of the Onset of Brain Failure by Electroencephalography. *Vet. Rec.* **2000**, *147*, 298–303. [\[CrossRef\]](#)
253. van de Vis, J.W.; Abbink, W.; Lambooi, B.; Bracke, M.B.M. Stunning and Killing of Farmed Fish: How to Put It into Practice? In *Encyclopedia of Meat Sciences*, 2nd ed.; Academic Press: Cambridge, MA, USA, 2014; pp. 421–426.
254. Roth, B.; Slinde, E.; Robb, D.H. Percussive Stunning of Atlantic Salmon (*Salmo salar*) and the Relation between Force and Stunning. *Aquac. Eng.* **2007**, *36*, 192–197. [\[CrossRef\]](#)
255. Ssubi, J.A.; Mukisa, I.M.; Muyanja, C.K. Compliance of Fishery Handling Facilities to Food Safety Requirements within the Fresh Nile Perch Value Chain in Uganda. *Cogent Food Agric.* **2024**, *10*, 2419439. [\[CrossRef\]](#)
256. Winton, J.R. *Fish Health Management. Fish Hatchery Management*, 2nd ed.; American Fisheries Society: Bethesda, MD, USA, 2001; pp. 559–640.
257. Roy, S.M.; Beg, M.M.; Moulick, S.; Kim, T. Sustainable Aquaculture: Enhancing Food Security with Energy Efficiency. In *Food Security, Nutrition and Sustainability Through Aquaculture Technologies*; Springer: Berlin/Heidelberg, Germany, 2025; pp. 363–373.
258. Vo, T.T.E.; Ko, H.; Huh, J.-H.; Park, N. Overview of Solar Energy for Aquaculture: The Potential and Future Trends. *Energies* **2021**, *14*, 6923. [\[CrossRef\]](#)
259. Gorjian, S.; Kamrani, F.; Fakhraei, O.; Samadi, H.; Emami, P. Emerging Applications of Solar Energy in Agriculture and Aquaculture Systems. In *Solar Energy Advancements in Agriculture and Food Production Systems*; Academic Press: Cambridge, MA, USA, 2022; pp. 425–469.
260. El-Sayed, S.M.; Youssef, A.M. Eco-Friendly Biodegradable Nanocomposite Materials and Their Recent Use in Food Packaging Applications: A Review. *Sustain. Food Technol.* **2023**, *1*, 215–227. [\[CrossRef\]](#)
261. Tsironi, T.; Houhoula, D.; Taoukis, P. Hurdle Technology for Fish Preservation. *Aquac. Fish.* **2020**, *5*, 65–71. [\[CrossRef\]](#)
262. Navarro-Segura, L.; Ros-Chumillas, M.; Martínez-Hernández, G.B.; López-Gómez, A. A New Advanced Packaging System for Extending the Shelf Life of Refrigerated Farmed Fish Fillets. *J. Sci. Food Agric.* **2020**, *100*, 4601–4611. [\[CrossRef\]](#) [\[PubMed\]](#)
263. Sivertsvik, M.; Jeksrud, W.K.; Rosnes, J.T. A Review of Modified Atmosphere Packaging of Fish and Fishery Products—Significance of Microbial Growth, Activities and Safety. *Int. J. Food Sci. Technol.* **2002**, *37*, 107–127. [\[CrossRef\]](#)
264. Kumar, P.; Ganguly, S. Role of Vacuum Packaging in Increasing Shelf-Life in Fish Processing Technology. *Asian J. Bio Sci.* **2014**, *9*, 109–112.
265. Pavón Losada, J.A.; Ferrando, M.; Moncada, V.; Operato, L.; Gomes, L.; Rosenow, P.; Hamd, W. Food Packaging Business Models as Drivers for Sustainability in the Food Packaging Industry. *Front. Sustain. Food Syst.* **2025**, *9*, 1563904. [\[CrossRef\]](#)
266. Lewis, S.G.; Boyle, M. The Expanding Role of Traceability in Seafood: Tools and Key Initiatives. *J. Food Sci.* **2017**, *82*, A13–A21. [\[CrossRef\]](#)
267. Yeşilsu, A.F.; Alak, G.; Alp Erbay, E.; Sağdıç, O.; Özoğul, F.; Demirkesen, İ.; Rathod, N.B.; Bozkurt, F.; Alasalvar, C.; Benjakul, S. Sustainable Horizons: A Review on Sustainable Processing, Quality Enhancement, and Safety Assurance in Aquatic Food Products. *Food Rev. Int.* **2025**, *41*, 1709–1737. [\[CrossRef\]](#)
268. Kamboj, S.; Gupta, N.; Bandral, J.D.; Gandotra, G.; Anjum, N. Food Safety and Hygiene: A Review. *Int. J. Chem. Stud.* **2020**, *8*, 358–368. [\[CrossRef\]](#)
269. Awuchi, C.G. HACCP, Quality, and Food Safety Management in Food and Agricultural Systems. *Cogent Food Agric.* **2023**, *9*, 2176280. [\[CrossRef\]](#)
270. Tzouros, N.E.; Arvanitoyannis, I.S. Implementation of Hazard Analysis Critical Control Point (HACCP) System to the Fish/Seafood Industry: A Review. *Food Rev. Int.* **2000**, *16*, 273–325. [\[CrossRef\]](#)
271. Reilly, A.; Käferstein, F. Food Safety Hazards and the Application of the Principles of the Hazard Analysis and Critical Control Point (HACCP) System for Their Control in Aquaculture Production. *Aquac. Res.* **1997**, *28*, 735–752. [\[CrossRef\]](#)
272. Zhang, H.; Gui, F. The Application and Research of New Digital Technology in Marine Aquaculture. *J. Mar. Sci. Eng.* **2023**, *11*, 401. [\[CrossRef\]](#)
273. Wu, Y.; Duan, Y.; Wei, Y.; An, D.; Liu, J. Application of Intelligent and Unmanned Equipment in Aquaculture: A Review. *Comput. Electron. Agric.* **2022**, *199*, 107201. [\[CrossRef\]](#)
274. Lindholm-Lehto, P. Water Quality Monitoring in Recirculating Aquaculture Systems. *Aquac. Fish Fish.* **2023**, *3*, 113–131. [\[CrossRef\]](#)
275. Kumar, S.; Paul, T.; Sarkar, P.; Kumar, K. Environmental Factors Affecting Aquatic Animal Health. In *Management of Fish Diseases*; Springer: Berlin/Heidelberg, Germany, 2025; pp. 171–188.
276. Baena-Navarro, R.; Carriazo-Regino, Y.; Torres-Hoyos, F.; Pinedo-López, J. Intelligent Prediction and Continuous Monitoring of Water Quality in Aquaculture: Integration of Machine Learning and Internet of Things for Sustainable Management. *Water* **2025**, *17*, 82. [\[CrossRef\]](#)
277. Plumb, J.A.; Hanson, L.A. *Health Maintenance and Principal Microbial Diseases of Cultured Fishes*; John Wiley & Sons: Hoboken, NJ, USA, 2010; ISBN 0-8138-1693-9.
278. Sapkota, A.; Sapkota, A.R.; Kucharski, M.; Burke, J.; McKenzie, S.; Walker, P.; Lawrence, R. Aquaculture Practices and Potential Human Health Risks: Current Knowledge and Future Priorities. *Environ. Int.* **2008**, *34*, 1215–1226. [\[CrossRef\]](#)

279. Seiler, C.; Berendonk, T.U. Heavy Metal Driven Co-Selection of Antibiotic Resistance in Soil and Water Bodies Impacted by Agriculture and Aquaculture. *Front. Microbiol.* **2012**, *3*, 399. [CrossRef]
280. Dillon, M.; Zaczek-Moczydlowska, M.A.; Edwards, C.; Turner, A.D.; Miller, P.I.; Moore, H.; McKinney, A.; Lawton, L.; Campbell, K. Current Trends and Challenges for Rapid Smart Diagnostics at Point-of-Site Testing for Marine Toxins. *Sensors* **2021**, *21*, 2499. [CrossRef]
281. Quintanilla-Villanueva, G.E.; Maldonado, J.; Luna-Moreno, D.; Rodríguez-Delgado, J.M.; Villarreal-Chiu, J.F.; Rodríguez-Delgado, M.M. Progress in Plasmonic Sensors as Monitoring Tools for Aquaculture Quality Control. *Biosensors* **2023**, *13*, 90. [CrossRef]
282. Edo, G.I.; Samuel, P.O.; Oloni, G.O.; Ezekiel, G.O.; Ikpekor, V.O.; Obasohan, P.; Ongulu, J.; Otunuya, C.F.; Opiti, A.R.; Ajakaye, R.S. Environmental Persistence, Bioaccumulation, and Ecotoxicology of Heavy Metals. *Chem. Ecol.* **2024**, *40*, 322–349. [CrossRef]
283. Hopkins, C.R.; Roberts, S.I.; Caveen, A.J.; Graham, C.; Burns, N.M. Improved Traceability in Seafood Supply Chains Is Achievable by Minimising Vulnerable Nodes in Processing and Distribution Networks. *Mar. Policy* **2024**, *159*, 105910. [CrossRef]
284. Bertolini, M.; Bevilacqua, M.; Massini, R. FMECA Approach to Product Traceability in the Food Industry. *Food Control* **2006**, *17*, 137–145. [CrossRef]
285. Rahman, L.F.; Alam, L.; Marufuzzaman, M.; Sumaila, U.R. Traceability of Sustainability and Safety in Fishery Supply Chain Management Systems Using Radio Frequency Identification Technology. *Foods* **2021**, *10*, 2265. [CrossRef] [PubMed]
286. Dadhaneeya, H.; Nema, P.K.; Arora, V.K. Internet of Things in Food Processing and Its Potential in Industry 4.0 Era: A Review. *Trends Food Sci. Technol.* **2023**, *139*, 104109. [CrossRef]
287. Clark, L.F. The Current Status of DNA Barcoding Technology for Species Identification in Fish Value Chains. *Food Policy* **2015**, *54*, 85–94. [CrossRef]
288. Di Pinto, A.; Marchetti, P.; Mottola, A.; Bozzo, G.; Bonerba, E.; Ceci, E.; Bottaro, M.; Tantillo, G. Species Identification in Fish Fillet Products Using DNA Barcoding. *Fish. Res.* **2015**, *170*, 9–13. [CrossRef]
289. Thompson, M.; Sylvia, G.; Morrissey, M.T. Seafood Traceability in the United States: Current Trends, System Design, and Potential Applications. *Compr. Rev. Food Sci. Food Saf.* **2005**, *4*, 1–7. [CrossRef]
290. Ta, M.D.-P.; Wendt, S.; Sigurjonsson, T.O. Applying Artificial Intelligence to Promote Sustainability. *Sustainability* **2024**, *16*, 4879. [CrossRef]
291. Bottema, M.J.; Bush, S.R.; Oosterveer, P. Assuring Aquaculture Sustainability beyond the Farm. *Mar. Policy* **2021**, *132*, 104658. [CrossRef]
292. Hambrey, J. The 2030 Agenda and the Sustainable Development Goals: The Challenge for Aquaculture Development and Management. In *FAO Fisheries and Aquaculture Circular*; FAO: Rome, Italy, 2017.
293. Allegra, S.; Loi, G.; Garrido Gamarro, E. Analysis of Food Safety Import Notifications and Relevant Standards and Regulations for Aquaculture Products With a Focus on Antimicrobial Residues and Use. *Aquac. Res.* **2024**, *2024*, 9427435. [CrossRef]
294. Shao, Z.J. Aquaculture Pharmaceuticals and Biologicals: Current Perspectives and Future Possibilities. *Adv. Drug Deliv. Rev.* **2001**, *50*, 229–243. [CrossRef]
295. Rasul, M.N.; Hossain, M.T.; Haider, M.N.; Hossain, M.T.; Reza, M.S. Disease Prevalence, Usage of Aquaculture Medicinal Products and Their Sustainable Alternatives in Freshwater Aquaculture of North-Central Bangladesh. *Vet. Med. Sci.* **2025**, *11*, e70276. [CrossRef]
296. Booncharoen, C.; Anal, A.K. Attitudes, Perceptions, and on-Farm Self-Reported Practices of Shrimp Farmers' towards Adoption of Good Aquaculture Practices (GAP) in Thailand. *Sustainability* **2021**, *13*, 5194. [CrossRef]
297. Kruijssen, F.; Newton, J.; Kuijpers, R.; Bah, A.; Rappoldt, A.; Nichols, E.; Kusumawati, R.; Nga, D.N. Assessment of Social Impact of GAA's 'Best Aquaculture Practices' Certification. *KIT R. Trop. Inst. Amst.* **2021**, 1–95. Available online: https://www.kit.nl/wp-content/uploads/2022/01/GAA_Report.pdf (accessed on 21 September 2025).
298. Schrobback, P.; Zhang, A.; Loechel, B.; Ricketts, K.; Ingham, A. Food Credence Attributes: A Conceptual Framework of Supply Chain Stakeholders, Their Motives, and Mechanisms to Address Information Asymmetry. *Foods* **2023**, *12*, 538. [CrossRef]
299. Bergleiter, S.; Meisch, S. Certification Standards for Aquaculture Products: Bringing Together the Values of Producers and Consumers in Globalised Organic Food Markets. *J. Agric. Environ. Ethics* **2015**, *28*, 553–569. [CrossRef]
300. Bush, S.R.; Belton, B.; Hall, D.; Vandergeest, P.; Murray, F.J.; Ponte, S.; Oosterveer, P.; Islam, M.S.; Mol, A.P.; Hatanaka, M. Certify Sustainable Aquaculture? *Science* **2013**, *341*, 1067–1068. [CrossRef]
301. Saha, C.K. Emergence and Evolution of Aquaculture Sustainability Certification Schemes. *Mar. Policy* **2022**, *143*, 105196. [CrossRef]
302. Beg, M.M.; Roy, S.M.; Ramesh, P.; Moulick, S.; Tiyyasha, T.; Bhagat, S.K.; Abdelrahman, H.A. Organic Aquaculture Regulation, Production, and Marketing: Current Status, Issues, and Future Prospects—A Systematic Review. *Aquac. Res.* **2024**, *2024*, 5521188. [CrossRef]
303. Fleming, A.; Wise, R.M.; Hansen, H.; Sams, L. The Sustainable Development Goals: A Case Study. *Mar. Policy* **2017**, *86*, 94–103. [CrossRef]

304. Powell, D.A.; Erdozain, S.; Dodd, C.; Costa, R.; Morley, K.; Chapman, B.J. Audits and Inspections Are Never Enough: A Critique to Enhance Food Safety. *Food Control* **2013**, *30*, 686–691. [[CrossRef](#)]
305. Okpala, C.O.R.; Korzeniowska, M. Understanding the Relevance of Quality Management in Agro-Food Product Industry: From Ethical Considerations to Assuring Food Hygiene Quality Safety Standards and Its Associated Processes. *Food Rev. Int.* **2023**, *39*, 1879–1952. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.