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The Digital Blue Carrier for a Post-Carbon Future – Curriculum Innovations in Aquaculture [DiBluCa]
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AQUACULTURE FOR A CLIMATE-RESILIENT FUTURE

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Aquaculture for a Climate-Resilient Future

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Preface

The contemporary world is undergoing rapid transformation. Indications that climate change is not a remote prospect, but a present reality, include rising temperatures, extreme weather events, ocean acidification, and fluctuations in sea levels. This phenomenon has far-reaching consequences for all aspects of society, impacting individuals, ecosystems, agricultural systems, and communities. Aquaculture, a constituent of fisheries, is a sector that is particularly susceptible to these changes. It is a vital source of protein for a growing global population and is regarded as a model for the future of sustainable food production.

The objective of this publication is to facilitate comprehension among readers regarding the repercussions of climate change on aquaculture and to emphasise the knowledge and solutions necessary to ensure the sector's resilient, ethical, and sustainable development. This nexus marks the convergence of scientific, technological, and practical domains, underscoring the paramount importance of human adaptability, collaboration, and the propensity to instigate change.

The present volume explores not only the consequences of environmental changes – such as thermal stress, disease outbreaks, feed efficiency, genetic adaptation, and the use of biotechnologies – but also the systems, methods, and policy measures that can help the sector move forward. Themes encompass the adaptation of recirculating aquaculture systems (RAS), the implementation of integrated multi-trophic aquaculture (IMTA), the management of feeding strategies under changing temperature regimes, and the utilisation of innovations to mitigate the effects of ocean acidification.

Nevertheless, the present publication is not exclusively concerned with systems and technologies. The focus of this study is on human subjects. This text concerns the students who are set to determine the blue economy of the future. The following discourse pertains to pedagogues who are tasked with the responsibility of instilling values in their students. The following discourse pertains to the endeavours of farmers and researchers in their quest for solutions on both local and global scales. This concerns all individuals who are concerned about the legacy that is to be left for posterity.

This publication was developed as part of the project entitled 'The Digital Blue Career for a Post-Carbon Future – Curriculum Innovations in Aquaculture'. This initiative is designed to encourage a more in-depth examination of the subject, promote the adoption of sustainable practices, and instill a sense of responsibility in all individuals. In the context of climate change, the practice of aquaculture must be considered in terms of both challenges and opportunities.

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Abbreviations

DHA – Docosahexaenoic Acid
EPA – Eicosapentaenoic Acid
FCR – Feed Conversion Ratio
FER – Feed Efficiency Ratio
GE – Gross Energy
GHG – Greenhouse Gases
HAB – Harmful Algal Bloom
IMTA – Integrated Multi-Trophic Aquaculture
LCA – Life Cycle Assessment
MO – Multi-objective Optimisation
NE – Net Energy
pH – a scale used to measure how acidic or basic water is
ppt – Parts Per Thousand
PUFA – Polyunsaturated Fatty Acids
RAS – Recirculating Aquaculture System
SCO – single-cell organisms.

CONTENT

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Chapter 1. Effects of Global Warming on Water Quality and Impact on Aquaculture

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Introduction

The rise in global temperatures due to climate change has a significant impact on aquatic ecosystems, particularly the metabolic and growth processes of aquatic species. Elevated temperatures accelerate metabolic rates, increasing the oxygen demands of aquatic organisms, which can lead to growth and reproductive challenges. This chapter examines the interplay between temperature changes and the physiological processes of aquatic species, offering insights into how these dynamics impact water quality and ecosystem health. Climate change also profoundly affects coastal and estuarine ecosystems, with salinity fluctuations emerging as a critical consequence. Melting polar ice and altered precipitation patterns contribute significantly to changes in salinity levels, particularly in regions near freshwater inflows. These fluctuations pose challenges for aquatic organisms that depend on stable salinity conditions, altering ecosystem dynamics and threatening biodiversity (Guimbeau et al., 2024; Mensah et al., 2025).

Salinity changes due to climate change further disrupt marine ecosystems. Variations in salinity, driven by the melting of polar ice, altered precipitation patterns, and increased evaporation rates, affect the distribution of marine species, impacting biodiversity and complicating aquaculture operations. Nutrient loading from agricultural runoff, industrial discharges, and urban pollution exacerbates eutrophication, leading to harmful algal blooms (HABs), oxygen depletion, and severe disruptions to marine and freshwater ecosystems. Eutrophication, increasingly prevalent due to anthropogenic influences and climate change, has widespread ecological and economic consequences (Zhang et al., 2024; Mensah et al., 2025).

The twin pressures of climate change and human activities increasingly threaten water availability and quality. Droughts and water scarcity, exacerbated by rising temperatures and unpredictable precipitation patterns, disrupt global hydrological cycles. Concurrently, degraded water quality due to pollution and mismanagement poses significant challenges for ecosystems and human populations (DeNicola et al., 2015; Moussa et al., 2025). Global warming also poses challenges for aquaculture by altering environmental conditions essential for aquatic species. As water temperatures rise, many species struggle to thrive outside their optimal thermal ranges, leading to reduced yields and increased mortality. Furthermore, warmer waters create ideal conditions for pathogens and parasites, exacerbating risks to aquaculture (DeNicola et al., 2015; Moussa et al., 2025). These interconnected issues have a significant impact on the sustainability and profitability of aquaculture.

The geographical distribution of aquaculture zones is being reshaped by global warming. Rising sea temperatures, shifting ocean currents, and changing precipitation patterns alter the suitability of traditional aquaculture regions. This shift necessitates strategic adaptations, such as relocating operations to newly suitable zones, while also confronting challenges posed by invasive species, which thrive in altered conditions and disrupt native ecosystems. These disruptions carry significant socio-economic and environmental consequences, necessitating immediate attention from policymakers, researchers, and industry stakeholders.

1. The Impact of Global Warming on Water Quality

1.1. Temperature Changes and Their Impact on Ecosystems

1.1.1. Mechanisms of Thermal Stratification and Oxygen Depletion

Thermal stratification occurs when differences in water temperature create distinct layers within a body of water. This process is exacerbated by global warming, as rising surface temperatures intensify the separation between warmer, lighter surface water and cooler, denser deep water. These layers impede vertical mixing, limiting the downward movement of oxygen and the upward movement of nutrients. Consequently, oxygen levels in deeper waters decline, leading to hypoxia or anoxic conditions, which have a severe impact on marine ecosystems (Bhuiyan et al., 2024; Burke et al., 2022).

Oxygen depletion has been particularly pronounced in areas with weak ventilation and high rates of organic matter decomposition. For example, the Eastern Tropical Pacific (ETP) and Arabian Sea exhibit extensive oxygen minimum zones (OMZs), where dissolved oxygen levels are below 20 μmol/L, spanning depths of 100 to 1,000 meters. These regions highlight the interplay between slow oceanic circulation, organic matter decay, and limited oxygen replenishment (Bhuiyan et al., 2024).

Regional and Global Trends

Globally, the oxygen content of oceans has declined by approximately 2% since 1960. This trend is attributed to intensified stratification, eutrophication, and warming. Coastal regions, including the Gulf of Mexico and Chesapeake Bay, have experienced significant expansions of hypoxic zones, commonly referred to as ‘dead zones’. These areas are primarily driven by nutrient runoff, which fuels algal blooms, resulting in increased organic matter decomposition and oxygen consumption (Bhuiyan et al., 2024).

Satellite-based models provide valuable insights into dissolved oxygen dynamics, showing how temperature and salinity variations correlate with oxygen levels. For instance, regions influenced by upwelling, such as the California Current, reveal higher oxygen variability due to the interplay of nutrient-rich cold waters and biological productivity (Sundararaman & Shanmugam, 2024).

Impacts on Marine Life

Oxygen depletion directly affects aquatic species by reducing habitable zones and altering ecosystem dynamics. Sessile organisms and benthic fauna suffer the most, as they cannot escape low-oxygen conditions. Fish and mobile invertebrates face habitat compression, forcing them into shallower, oxygen-rich layers, which increases competition and predation risk. Furthermore, prolonged hypoxia can disrupt reproduction and growth, leading to population declines in commercially important species (Burke et al., 2022; Sundararaman & Shanmugam, 2024).

Mitigation Strategies

1. **Enhanced Monitoring**. Advances in remote sensing and biogeochemical models provide real-time data on oxygen and nutrient dynamics, facilitating the early detection of hypoxic conditions.

2. **Nutrient Management**. Reducing agricultural runoff and implementing sustainable farming practices can mitigate eutrophication and its associated oxygen depletion.

3. **Oxygenation Systems**. In aquaculture, technologies such as liquid oxygen injection and aeration systems have been employed to alleviate low-oxygen stress in fish farms, with mixed success depending on environmental conditions (Burke et al., 2022).

4. **Climate Mitigation**. Addressing the root causes of global warming through reduced carbon emissions is critical for reversing stratification trends and preserving marine biodiversity (Bhuiyan et al., 2024).

1.1.2. Metabolic Rates and Oxygen Demand

Higher temperatures directly influence metabolic rates in aquatic organisms, driving an increase in oxygen consumption to meet heightened energy demands. Studies indicate that temperature-dependent hypoxia poses a significant challenge, as oxygen availability decreases with rising temperatures, thereby limiting the aerobic capacities of organisms (Seibel, 2024). For instance, the Metabolic Index demonstrates that oxygen supply becomes insufficient to meet demand at higher temperatures, restricting growth and reproduction (Deutsch et al., 2020).

Fish species are particularly vulnerable, as elevated metabolic rates necessitate greater oxygen intake, which is difficult to achieve in warmer waters with reduced oxygen solubility. This physiological stress not only hampers growth but also affects survival rates, particularly for species inhabiting shallow or thermally stratified environments (Okon et al., 2024).

Growth and Reproductive Challenges

Temperature increases significantly alter the growth trajectories and reproductive cycles of aquatic species. For many fish species, warmer waters lead to earlier maturation but shorter lifespans, disrupting population dynamics and ecosystem balance (Liu et al., 2024). Moreover, elevated temperatures can impair gamete quality and reduce spawning success, thereby decreasing reproductive output. For example, species in the Northwest Pacific have exhibited changes in their reproductive strategies as a direct response to shifting thermal regimes, emphasising the profound influence of temperature on life history traits (Liu et al., 2024).

Impacts on Ecosystem Health

The cascading effects of metabolic and growth changes extend to broader ecosystem health. Increased metabolic rates lead to greater nutrient uptake and waste excretion, which can exacerbate eutrophication in waters that are already nutrient-rich. Additionally, thermal stress can weaken immune responses, making species more susceptible to pathogens and diseases, as observed in global aquaculture systems (Okon et al., 2024). These interactions underline the critical need for integrated management strategies to mitigate climate-induced stressors on aquatic ecosystems.

Adaptive Responses and Mitigation Strategies

Aquatic species exhibit varying degrees of phenotypic plasticity to cope with thermal stress. Euryhaline species, for instance, adjust their osmoregulatory mechanisms to manage increased salinity and temperature fluctuations (Esbaugh, 2025). However, the extent of such adaptations is limited by energetic constraints, highlighting the importance of proactive measures to mitigate temperature impacts.

Effective strategies include restoring riparian vegetation to shade water bodies, reducing thermal loading, and enhancing water flow in stratified systems to improve oxygen distribution. Furthermore, global efforts to curb greenhouse gas emissions remain crucial in addressing the root causes of climate-induced temperature increases (Seibel, 2024).

1.2. Chemical Composition: Acidity, Salinity, and Nutrients

1.2.1. pH Levels and Ocean Acidification

The absorption of carbon dioxide (CO_2) by oceans is a primary driver of ocean acidification, causing a measurable decline in pH levels. Since the pre-industrial era, surface ocean pH has decreased by approximately 0.1 units, representing a 26% increase in hydrogen ion concentration (Duarte et al., 2022). This acidification results from CO_2 combining with seawater to form carbonic acid, which dissociates into bicarbonate and hydrogen ions, lowering pH and reducing carbonate ion availability (Grabba et al., 2024). Carbonate ions are essential for calcifying organisms, such as shellfish and corals, to build and maintain their calcium carbonate structures. Reduced carbonate availability has been linked to thinner, weaker shells and diminished skeletal integrity in marine species (Andreyeva et al., 2024).

Ocean acidification has a severe impact on calcifying organisms, which are particularly sensitive to changes in carbonate saturation states. Laboratory studies on bivalves, such as mussels and oysters, demonstrate that reduced pH conditions impede shell formation, delay development, and increase mortality rates during early life stages (Hamilton et al., 2022). For instance, the mussel *Mytilus* *galloprovincialis* has shown resilience to low pH but still experiences increased shell injuries and decreased growth rates under acidified conditions (Andreyeva et al., 2024). Such physiological stresses compromise the survival and performance of these species in both natural habitats and aquaculture systems.

Ocean acidification also impairs non-calcifying species by altering sensory functions, growth, and reproduction. Behavioural changes, such as reduced predator avoidance and altered habitat preferences, have been observed in fish and invertebrates under low pH conditions (Grabba et al., 2024). Furthermore, acidification combined with other stressors, such as hypoxia, exacerbates these adverse effects, leading to a compounding impact on marine biodiversity (Andreyeva et al., 2024).

Economic and Ecological Consequences

The economic ramifications of ocean acidification are profound, particularly for industries reliant on calcifying organisms. Shellfish fisheries and aquaculture face significant challenges, with projected losses in production and market value due to compromised shell quality and survival rates (Mangi et al., 2018). In the United Kingdom, the economic losses attributed to ocean acidification could range from 14% to 28% of fishery net present value under high-emission scenarios (Mangi et al., 2018). These economic pressures underscore the urgency of addressing acidification to safeguard marine resources and livelihoods.

From an ecological perspective, the disruption of marine food webs is a critical concern. Reduced populations of calcifying organisms can have cascading effects on predator-prey dynamics, nutrient cycling, and overall ecosystem stability (Duarte et al., 2022). Integrated approaches, such as multi-trophic aquaculture systems, have shown promise in mitigating these impacts by utilising seaweeds to buffer pH levels and support calcifying species (Hamilton et al., 2022).

Mitigation Strategies and Future Outlook

Addressing ocean acidification requires coordinated global efforts to reduce CO_2 emissions and implement adaptive strategies. Restoring seagrass meadows and mangroves can enhance coastal resilience by absorbing CO_2 and providing habitats for marine organisms (Hamilton et al., 2022). Additionally, advancing aquaculture practices to incorporate pH buffering techniques, such as the use of seaweed, can mitigate acidification's impact on shellfish farming (Hamilton et al., 2022).

Long-term monitoring and research are essential for comprehending the complex effects of acidification and developing effective policies. Enhanced international cooperation and the integration of scientific findings into policy frameworks, such as the Kunming-Montreal Global Biodiversity Framework, are essential for mitigating acidification and protecting marine biodiversity (Grabba et al., 2024).

1.2.2. Changes in Salinity

The primary drivers of salinity fluctuations include freshwater inflows from glacial melt, increased precipitation, and seasonal variations in river discharge. For example, in the Northern Gulf of Alaska, freshwater inputs from glaciated watersheds contribute to marked seasonal and spatial variations in salinity. These changes are further modulated by wind-driven mixing and coastal currents, which influence the distribution of freshwater plumes (Reister et al., 2024). Similarly, the Bering Sea has experienced significant freshening due to reduced sea ice production and increased meltwater volumes, leading to weakened stratification and shifts in nutrient cycling (Mensah et al., 2025).

Impacts on Marine and Estuarine Organisms

Organisms inhabiting estuarine and coastal regions are susceptible to salinity fluctuations. For species reliant on stable salinity, such as shellfish and specific fish populations, shifts in salinity can disrupt physiological processes, including osmoregulation, growth, and reproduction (Guimbeau et al., 2024). For instance, studies in Bangladesh reveal that increased salinity exposure during critical developmental periods leads to stunted growth in children, highlighting the broader socio-ecological consequences of salinity changes (Guimbeau et al., 2024).

Estuarine systems, like those in the Chesapeake Bay, face compounded stress from nutrient enrichment and salinity changes. Elevated salinity levels have been linked to reduced species diversity and shifts in community composition, as less tolerant species are replaced by opportunistic generalists (Zhang et al., 2024). This reduction in biodiversity has cascading effects on food web stability and ecosystem services.

Broader Ecological and Socioeconomic Consequences

Salinity fluctuations affect not only biodiversity but also the productivity of coastal fisheries and aquaculture. For instance, saltwater intrusion into freshwater systems reduces the availability of habitats suitable for freshwater and brackish species. In aquaculture, fluctuating salinity complicates the maintenance of optimal conditions, impacting the growth and survival of cultivated species (Mensah et al., 2025).

Furthermore, these changes exacerbate existing vulnerabilities in coastal communities. Reduced agricultural productivity in regions like the Ganges-Brahmaputra delta has been linked to the salinisation of irrigation water, underscoring the socio-economic ripple effects of salinity fluctuations (Guimbeau et al., 2024).

Mitigation and Adaptive Strategies

Addressing the impacts of salinity fluctuations requires integrated management strategies. Restoring coastal vegetation, such as mangroves and seagrasses, can buffer salinity changes by stabilising sediments and enhancing water retention. Additionally, improved modelling of freshwater inflows and salinity dynamics can inform adaptive management practices, such as modifying irrigation schedules and selecting salt-tolerant crop varieties (Zhang et al., 2024).

At a broader scale, reducing greenhouse gas emissions is crucial for mitigating the underlying drivers of climate change. Investments in global monitoring systems and community-level adaptation plans can further enhance resilience to salinity changes in vulnerable regions (Guimbeau et al., 2024; Mensah et al., 2025).

Mechanisms of Salinity-Induced Distribution Shifts

Salinity fluctuations are primarily driven by freshwater inflows, glacial melt, and changing precipitation patterns. For example, coastal regions near estuaries experience significant salinity variability due to seasonal and climatic changes (Guimbeau et al., 2024). In Western Australian estuaries, hypersalinity develops when freshwater inflows decline, and evaporation exceeds water inputs, forcing species to migrate to less saline areas or face population declines (Hoeksema et al., 2023).

Marine organisms exhibit varying tolerances to changes in salinity, which influence their distribution. Euryhaline species, which are capable of adapting to wide salinity ranges, dominate areas with fluctuating salinity levels. However, stenohaline species, which require stable salinity levels, often retreat to refugia or experience population declines when salinity levels deviate from optimal levels (Rahman & Hung, 2024).

Impacts on Species Distribution and Aquaculture

Salinity changes significantly alter the spatial distribution of marine species. For instance, the deep-water rose shrimp *Parapenaeus longirostris* in the Mediterranean Sea has shifted its range in response to warming and salinisation, with populations moving northward and deeper to avoid less favourable conditions (Mingote et al., 2024). These shifts disrupt local ecosystems and fisheries by altering predator-prey dynamics and resource availability.

Aquaculture operations also face challenges due to variations in salinity. Species like smelt, which are sensitive to salinity during reproduction, exhibit reduced sperm motility and fertilisation success under non-optimal salinity conditions. This affects hatchery operations and the sustainability of aquaculture practices (Rahman & Hung, 2024). In Bangladesh, progressive salinisation has constrained aquaculture productivity and led to increased socioeconomic vulnerability in coastal communities (Guimbeau et al., 2024).

Broader Ecological and Socioeconomic Implications

Salinity-driven species distribution shifts have cascading effects on ecosystem services. Changes in community composition affect nutrient cycling, primary production, and the stability of marine food webs (Hoeksema et al., 2023). For instance, as hypersalinity develops in estuaries, the abundance of estuarine-resident species declines, leading to reduced biodiversity and altered ecosystem functioning.

Economically, fisheries reliant on specific species face uncertainties as target populations migrate to less accessible areas. This has been observed in the Mediterranean, where changes in salinity and temperature have impacted the availability of economically valuable species, such as the rose shrimp (Mingote et al., 2024). Additionally, salinity fluctuations pose significant challenges for aquaculture, necessitating investments in adaptive infrastructure and practices to mitigate their impacts on production.

Mitigation Strategies and Future Directions

Addressing the impacts of salinity changes on marine species distribution requires integrated management strategies that consider the effects on both species and their habitats. Efforts should focus on reducing greenhouse gas emissions to mitigate climate change and stabilise environmental conditions. Restoring coastal vegetation, such as mangroves and seagrasses, can buffer salinity changes and provide habitat for marine organisms (Guimbeau et al., 2024).

Aquaculture operations can benefit from technological innovations, such as recirculating aquaculture systems (RAS) and selective breeding of salt-tolerant species. Improved monitoring and predictive models of salinity changes can also inform adaptive management strategies, ensuring the resilience of aquaculture and fisheries to salinity-induced challenges (Rahman & Hung, 2024).

1.2.3. Mechanisms of Nutrient Loading and Eutrophication

Excess nutrients, particularly nitrogen and phosphorus, are introduced into aquatic systems *via* runoff from agricultural lands, urban wastewater, and industrial effluents. These nutrients promote the growth of phytoplankton and algae, leading to algal blooms that deplete oxygen levels as they decompose (Reister et al., 2024). In the Gulf of Mexico, nutrient loading from the Mississippi River basin has created one of the largest hypoxic zones globally, impacting fisheries and biodiversity (Day et al., 2024).

Climate change exacerbates nutrient loading through increased precipitation and extreme weather events, which enhance nutrient runoff into water bodies. Rising temperatures further contribute to eutrophication by accelerating algal growth and altering ecosystem dynamics (Mensah et al., 2025). These compounded effects intensify the frequency and duration of HABs, which release toxins that are harmful to both marine life and human health (Zhang et al., 2024).

Impacts of Eutrophication

Eutrophication profoundly affects aquatic ecosystems by disrupting food webs and reducing biodiversity. Oxygen depletion, or hypoxia, forces fish and invertebrates to migrate or face mortality, while benthic habitats suffer from sediment anoxia (Reister et al., 2024). For example, studies in the Chesapeake Bay reveal significant declines in fish populations due to recurrent hypoxic events (Zhang et al., 2024).

HABs pose additional challenges by producing toxins that affect marine organisms and human populations. Species such as *Karenia brevis* and *Microcystis aeruginosa* have been linked to massive fish kills, shellfish contamination, and respiratory issues in humans (Mensah et al., 2025). Economic losses from HABs are substantial, particularly for fisheries, tourism, and public health.

Mitigation Strategies

Effective mitigation of nutrient loading and eutrophication requires integrated watershed management and policy interventions. Reducing agricultural runoff through sustainable farming practices, such as cover cropping, buffer zones, and precision fertilisation, can significantly decrease nutrient inputs (Reister et al., 2024). Urban areas can benefit from advanced wastewater treatment technologies that remove excess nutrients before they are discharged.

Restoration of wetlands and riparian zones offers natural solutions by filtering nutrients and improving water quality. Additionally, public education and policy reforms, including nutrient management regulations and incentives for sustainable practices, are critical for addressing the root causes of eutrophication (Day et al., 2024).

1.3. Hydrological Extremes and Their Consequences for Water Quality

1.3.1. Drivers of Droughts and Water Scarcity

Droughts are primarily driven by climatic variations, including reduced precipitation and rising temperatures, which intensify evapotranspiration. Human activities, such as unsustainable water withdrawals and land degradation, further exacerbate these natural phenomena (Zucca et al., 2021). For example, in arid regions like Saudi Arabia, decades of groundwater overextraction and poor irrigation practices have depleted critical aquifers, compounding the effects of natural water scarcity (DeNicola et al., 2015).

Climate change exacerbates these challenges by altering precipitation patterns, resulting in more frequent and severe droughts. The Gulf Cooperation Council (GCC) countries, characterised by hyper-arid climates, are particularly vulnerable. Rapid urbanization and population growth in these regions increase water demand, straining already limited resources. Innovative strategies, such as wastewater recycling and desalination, have been adopted to address these issues, but they remain energy-intensive and environmentally taxing (Moussa et al., 2025).

1.3.2. Impacts of Degraded Water Quality

Degraded water quality often coincides with scarcity, as limited resources become increasingly polluted by agricultural runoff, industrial discharges, and urban effluents. For instance, excessive nutrient loading in river basins leads to eutrophication, harmful algal blooms, and hypoxic conditions, which disrupt aquatic ecosystems and threaten biodiversity (Giri, 2021). In Saudi Arabia, extreme weather events linked to climate change exacerbate water contamination, introducing pathogens and pollutants into freshwater sources (DeNicola et al., 2015).

The socio-economic consequences of degraded water quality are profound. Poor water quality complicates treatment processes, raises costs, and undermines public health. Globally, waterborne diseases resulting from contaminated drinking water are a leading cause of morbidity and mortality, particularly in low-income communities (Giri, 2021). In the GCC, water scarcity-driven reductions in agricultural output pose a threat to food security, highlighting the cascading effects of water quality issues (Moussa et al., 2025).

Mitigation Strategies

Addressing the dual challenges of drought and degraded water quality requires an integrated approach that combines technological innovation, policy reforms, and community engagement.

Sustainable water management practices, such as rainwater harvesting and efficient irrigation systems, are crucial for reducing reliance on overexploited water sources (Moussa et al., 2025). Restoring natural ecosystems, including wetlands, can improve water quality by filtering pollutants and regulating hydrological cycles (Zucca et al., 2021).

Advancements in desalination technology and wastewater treatment offer potential solutions for water-scarce regions. However, these technologies must be deployed sustainably to minimise environmental impacts and ensure accessibility for vulnerable populations. International collaboration and capacity building are crucial for sharing knowledge and resources to address global water challenges (DeNicola et al., 2015).

2. The Impact of Global Warming on Aquaculture

1.4. Ecological and Economic Species Vulnerability

1.4.1. Temperature Sensitivity and Species Vulnerability

Aquatic species depend on stable water temperatures for physiological and metabolic processes. Deviations from optimal ranges can impair growth, reproduction, and survival. For instance, tropical species such as shrimp and tilapia are particularly vulnerable to temperature fluctuations, which disrupt enzymatic activities and metabolic efficiency (Giri, 2021). Studies show that prolonged exposure to temperatures outside a species' tolerance limits can lead to stress-induced mortality and lower aquaculture yields (DeNicola et al., 2015).

In regions such as the Arabian Peninsula, where water temperatures are rising faster than the global average, aquaculture faces compounding challenges. Higher temperatures not only reduce dissolved oxygen levels but also increase ammonia toxicity, further threatening aquatic health (Moussa et al., 2025). These effects underscore the need for adaptive measures, such as selective breeding for temperature-resistant species and the development of aquaculture systems that regulate thermal environments.

Disease and Parasite Proliferation

Warmer water temperatures accelerate the life cycles of pathogens and parasites, leading to more frequent and severe outbreaks. For instance, diseases caused by *Vibrio* spp. and parasites, such as sea lice, thrive in elevated temperatures, resulting in significant economic losses in aquaculture (Zucca et al., 2021). The increased prevalence of these threats has been documented in shrimp farms across Southeast Asia and salmon farms in the North Atlantic, where rising sea surface temperatures have facilitated the spread of infectious diseases (DeNicola et al., 2015).

The relationship between temperature and disease dynamics is further complicated by climate-induced changes in water chemistry, including acidification and shifts in salinity. These factors can weaken host resistance, making species more susceptible to infections (Giri, 2021). Effective disease management in aquaculture thus requires a combination of improved monitoring systems, biosecurity measures, and research into disease-resistant strains.

Mitigation and Adaptation Strategies

Addressing the impacts of global warming on aquaculture requires proactive and integrated strategies. Technological innovations, such as recirculating aquaculture systems (RAS) and temperature-controlled ponds, can mitigate thermal stress on aquatic species (Moussa et al., 2025). Additionally, implementing vaccination programs and advancing disease detection technologies can help manage pathogen risks.

Policymakers and stakeholders must also prioritise environmental conservation to stabilise ecosystems. Restoring mangroves and wetlands, for example, can buffer aquaculture farms from the effects of temperature fluctuations and provide natural filtration for pathogens. Furthermore, fostering international collaboration on climate-resilient aquaculture practices will be essential to sustaining this vital industry under changing environmental conditions (Zucca et al., 2021).

1.4.2. Economic Consequences of Global Warming Impact on Aquaculture

Global warming disrupts the balance of aquatic ecosystems, directly affecting fish and shellfish populations. Rising sea temperatures, acidification, and changing ocean currents alter the habitats and physiology of aquatic species. For example, ocean warming reduces oxygen availability in water, stressing marine life and leading to lower growth rates and reproductive success (Baag & Mandal, 2022). These stressors result in significant declines in fish stocks and shellfish yields, with cascading effects on aquaculture profitability (Doney et al., 2009).

The combined effects of warming and acidification significantly impair the calcification processes in shellfish, such as oysters and clams. Reduced pH levels hinder their growth and survival, jeopardising their availability for aquaculture. Studies have shown that calcifying organisms are particularly vulnerable to declining carbonate ion concentrations caused by increased atmospheric CO_2 (Nienhuis et al., 2010). As a result, aquaculture operators face the dual challenge of mitigating environmental impacts and maintaining production levels.

Declining Water Quality and Disease Outbreaks

Water quality is a critical factor in aquaculture, and climate change exacerbates its deterioration. Increased sea temperatures promote the proliferation of harmful algal blooms (HABs), which deplete oxygen levels and release toxins harmful to aquatic species. These blooms, driven by nutrient-rich runoff and warming waters, have been linked to massive fish die-offs and economic losses in aquaculture (USEPA, 2014).

Additionally, higher water temperatures accelerate the spread of diseases among aquatic species. Pathogens thrive in warmer conditions, leading to increased disease outbreaks in aquaculture systems. For instance, studies on oyster aquaculture have revealed that warming temperatures weaken oyster immunity and increase susceptibility to infections, thereby reducing survival rates and production output (Neokye et al., 2024). These factors collectively decrease the economic viability of aquaculture operations by increasing mortality rates and treatment costs.

Adaptation Costs

Adapting to climate-induced challenges requires significant investments in infrastructure and management practices. Aquaculture facilities must incorporate resilient technologies, such as temperature-controlled systems and disease-resistant species, to maintain production levels. However, these adaptations come at substantial costs, which can strain the financial resources of aquaculture operators, particularly in low-income regions (Naylor et al., 2023).

The shifting geographic distribution of suitable aquaculture sites further underscores the need for adaptive measures. Rising sea levels and extreme weather events necessitate the relocation of aquaculture operations to areas with more stable conditions, thereby adding to the economic burden. Moreover, policies aimed at mitigating environmental impacts, including stricter regulations on waste management and resource use, require investments in compliance measures and advanced technologies (Garlock et al., 2022).

Regional and Global Impacts

The economic consequences of global warming on aquaculture are unevenly distributed. Regions with highly vulnerable ecosystems, such as the tropics, face more pronounced challenges. High salinity, drought, and invasive species disrupt aquaculture activities, particularly for species like shrimp and tilapia. Conversely, temperate regions experience relatively moderate impacts but are not immune to the long-term effects of climate change, such as altered precipitation patterns and increased frequency of storms (Mahu et al., 2022).

Globally, the demand for aquaculture products continues to rise, driven by population growth and the need for sustainable protein sources. This creates a paradoxical situation where the aquaculture sector must scale up production to meet demand while grappling with the economic and environmental costs of climate adaptation. Failure to address these challenges risks exacerbating food insecurity and economic disparities (FAO, 2022).

Policy and Governance

Effective policy frameworks are crucial for mitigating the economic impacts of global warming on aquaculture. Governments and international organisations must implement strategies to support sustainable practices and promote research into resilient aquaculture systems. For example, investments in genetic research to develop climate-resilient species and the establishment of early warning systems for HABs can reduce vulnerabilities and enhance sectoral resilience (Handisyde et al., 2017).

Furthermore, integrating aquaculture policies into broader climate action plans ensures a coordinated approach to addressing these challenges. Policies should strike a balance between economic growth and environmental sustainability, enabling aquaculture operators to adapt without compromising ecological integrity (Naylor et al., 2023).

1.5. Geographic Redistribution and Climate Adaptation

1.5.1. Shifting Zones: Relocation of Suitable Aquaculture Areas

Climate change-induced environmental changes are leading to the displacement of aquaculture zones. Rising ocean temperatures are pushing species and operations poleward, as many traditional aquaculture areas become less viable due to thermal stress and reduced water quality (Zarzyczny et al., 2024). The tropicalisation of marine environments exemplifies this phenomenon, where tropical species expand into temperate regions, altering ecosystem structures and creating novel communities (Zarzyczny et al., 2024).

In addition to temperature changes, shifting precipitation patterns and freshwater availability influence inland aquaculture. For example, reduced water flow and increased salinity in estuarine regions affect the growth of species that rely on specific salinity levels (Priya et al., 2023). As a result, aquaculture operations face increased costs associated with relocating to regions with more stable and suitable environmental conditions (Mdoe et al., 2025). This relocation often requires detailed environmental assessments to identify areas that can sustainably support aquaculture while minimising ecological degradation.

Moreover, the relocation process is not just a technical challenge but also a socio-economic one. Many communities that rely on aquaculture for their livelihoods may face displacement or job losses if operations relocate. Efforts to mitigate such impacts require stakeholder engagement, retraining programs, and support for alternative livelihood options.

Invasive Species: Ecological and Operational Disruptions

Altered climatic conditions enable the proliferation of invasive species, which compete with native species and disrupt aquaculture operations. For instance, the tropicalisation of temperate zones facilitates the establishment of invasive species such as lionfish and certain types of algae, which can outcompete native organisms and degrade ecosystem health (Woods et al., 2016). These invasions often require aquaculture operators to implement costly management strategies to maintain production levels.

Furthermore, the arrival of invasive pathogens, facilitated by rising temperatures and global trade, increases the prevalence of disease outbreaks. This is particularly concerning for high-value species, such as shrimp and salmon, which are vulnerable to infections in warmer waters (Ross et al., 2023). Addressing these challenges requires significant investment in biosecurity measures, including the development of improved monitoring systems and the creation of pathogen-resistant breeds. Advanced biotechnological tools, such as CRISPR-based gene editing, are being explored to enhance disease resistance in aquaculture species.

Invasive species also disrupt the natural balance of ecosystems, leading to a loss of biodiversity. For example, invasive algae can form dense mats that smother coral reefs and seagrass beds, essential habitats for many marine organisms. The ecological ramifications extend beyond aquaculture, affecting fisheries, tourism, and overall marine biodiversity.

1.5.2. Adaptation Strategies

Adapting to these challenges involves a combination of technological innovation, policy intervention, and ecosystem-based approaches. Key strategies include:

1. **Integrated Multi-Trophic Aquaculture** (IMTA). By incorporating species from different trophic levels, IMTA systems mitigate the impacts of invasive species and enhance ecological resilience (Mdoe et al., 2025). This approach also maximises resource efficiency by recycling nutrients within the system.

2. **Genetic Improvements**. Developing breeds that are more tolerant to temperature fluctuations and diseases is a crucial step in ensuring the sustainability of aquaculture operations (Ross et al., 2023). Selective breeding programs and genomic tools are being used to create strains of fish and shellfish that can thrive under changing environmental conditions.

3. **Enhanced Monitoring and Early Warning Systems**. Real-time data collection and predictive modelling can help operators anticipate and respond to changes in environmental conditions and invasive species outbreaks (Wang et al., 2021). For instance, satellite imagery and AI-driven analytics are increasingly being used to monitor ocean temperatures, algal blooms, and other critical parameters.

4. **Policy and Regulation**. Implementing and enforcing robust policies that promote sustainable practices and protect biodiversity is critical. For example, policies aimed at managing invasive species and preventing their spread can reduce ecological and economic damages (Priya et al., 2023). Collaborative international frameworks, such as the United Nations' Sustainable Development Goals, can provide guidance and support for such efforts.

5. **Community Engagement**. Successful adaptation requires the involvement of local communities in decision-making processes. Empowering communities through education and capacity-building initiatives ensures that adaptation strategies are both practical and equitable.

Regional Variations in Impact

The impacts of global warming on aquaculture zones vary significantly across different regions. Tropical regions, which are already experiencing high temperatures, face the most significant challenges as they become less suitable for traditional aquaculture species. Conversely, temperate regions are seeing an influx of tropical species, which presents opportunities for diversification but also risks associated with ecosystem imbalance (Zarzyczny et al., 2024).

Coastal regions are particularly vulnerable to sea level rise and storm surges, which damage aquaculture infrastructure and disrupt production cycles. In response, some operations are relocating to inland or offshore areas with more stable conditions, though this transition involves substantial costs and logistical complexities (Woods et al., 2016). Offshore aquaculture, while promising, requires advancements in engineering to withstand harsh ocean conditions and reduce environmental footprint.

Regions with strong governance and research capabilities, such as those in Northern Europe and North America, are better positioned to adapt to these challenges. In contrast, low-income regions, particularly in the Global South, face significant barriers, including limited access to funding, technology, and expertise. Addressing these disparities is crucial to ensuring global food security and equitable development.

Summary

Thermal stratification and oxygen depletion pose significant threats to aquatic ecosystems, with extensive ecological and economic consequences. Understanding the interplay of physical, chemical, and biological processes that drive these changes is essential for developing effective mitigation strategies. By integrating technological advancements and sustainable practices, the impacts of global warming on aquatic systems can be better managed.

Rising global temperatures pose significant challenges to aquatic species, increasing their metabolic demands and leading to issues with growth and reproduction. These physiological changes not only threaten individual species but also compromise the integrity of ecosystems. A comprehensive understanding of these dynamics, coupled with targeted mitigation efforts, is critical to safeguarding aquatic biodiversity and maintaining water quality in a changing climate.

Climate-induced salinity fluctuations have a significant impact on coastal and marine ecosystems, disrupting species distributions and aquaculture operations, while posing challenges to the communities that depend on them. Addressing these impacts requires a holistic approach that integrates ecological and socio-economic considerations. By prioritising adaptive strategies, including sustainable management practices and robust policy frameworks, it is possible to mitigate these challenges and safeguard biodiversity and livelihoods.

Nutrient loading and eutrophication continue to be critical threats to aquatic ecosystems, driving harmful algal blooms, oxygen depletion, and ecosystem degradation. Effective mitigation strategies must focus on reducing nutrient inputs, restoring ecosystem balance, and fostering collaboration among stakeholders, policymakers, and scientists to achieve sustainable outcomes.

Water scarcity, exacerbated by global warming and human activities, poses significant challenges for global water security. Droughts, unpredictable precipitation patterns, and degraded water quality pose significant threats to both ecosystems and human populations. Prioritising sustainable water management practices, fostering international cooperation, and implementing innovative solutions are essential to mitigate these challenges and protect vital water resources for future generations.

Global warming also profoundly impacts aquaculture, increasing the vulnerability of species to temperature fluctuations and escalating disease and parasite risks. These challenges have far-reaching implications for food security and the economic stability of coastal communities. Collaborative efforts between researchers, policymakers, and industry stakeholders are necessary to develop and implement innovative solutions that enhance resilience and sustainability in the aquaculture industry.

The geographical redistribution of aquaculture zones due to climate change necessitates proactive adaptation strategies. Rising sea temperatures, shifting currents, and altered precipitation patterns demand the relocation of operations and the adoption of sustainable practices. Integrating traditional ecological knowledge with modern scientific advancements can create holistic solutions to these challenges, ensuring the resilience of the aquaculture industry and its continued contribution to global food security.

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Chapter 2. Environmental Impacts of Aquaculture from a Global Warming Perspective

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Introduction

In the face of climate change, the environmental impact of aquaculture is a growing concern, as the industry contributes to greenhouse gas emissions, habitat destruction, and resource depletion. Greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, contribute significantly to global warming by trapping heat in the Earth's atmosphere. While CO_2 often takes centre stage, CH_4 is a highly potent greenhouse gas whose increased emissions are caused by human activities such as deforestation, mining, biomass burning, and industrial processes (Wróbel et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) has emphasised that the human impact on climate change is undeniable, with industrialization and urbanization leading to record-breaking greenhouse gas emissions. The transport, energy, and agriculture sectors continue to contribute significantly to climate change, affecting weather patterns, sea levels, and biodiversity.

While the global aquaculture industry is crucial for food security, it is also a significant contributor to greenhouse gas emissions. Energy-intensive operations, land-use change, feed production, and waste management contribute to its carbon footprint (MacLeod et al., 2019). Many aquaculture facilities rely on electricity from fossil fuels, which increases CO_2 emissions, especially in regions where coal, oil, and natural gas dominate energy production (Bujas et al., 2022). Furthermore, the rapid expansion of the industry has led to habitat conversion, particularly in ecologically sensitive areas such as mangroves and wetlands, resulting in biodiversity loss and ecosystem degradation (Barbier et al., 2011).

One of the most significant environmental impacts of aquaculture is feed production, which accounts for up to 90% of greenhouse gas emissions in fish farming (FAO, 2022). The cultivation of feed, including fishmeal and plant-based ingredients, requires a lot of land, water, and energy, which further exacerbates environmental problems. In addition, aquaculture generates considerable waste, including uneaten feed, faeces, metabolic by-products, and chemical residues, all of which can affect water quality and disrupt aquatic ecosystems (Wu, 1995; Dalsgaard & Krause-Jensen, 2006; Holmer et al., 2008). The extent of these impacts varies depending on the location of the farm, species grown, stocking density, and feed efficiency. As the global demand for seafood continues to increase, it is an urgent challenge to reconcile the growth of aquaculture with environmental sustainability. Sustainable practices in energy use, land management, feed production, and waste treatment are essential to minimise the industry's carbon footprint and ensure long-term environmental viability.

1. Greenhouse Gases and Carbon Footprint

Greenhouse gas (GHG) emissions significantly impact Earth's atmosphere by trapping heat. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. While CO_2 is frequently discussed, CH_4 also plays a crucial role in global warming. Anthropogenic activities, such as wetland conversion, landfilling, dam construction, biomass burning, deforestation, mining, and the extraction of gas and coal, have significantly increased CH_4 emissions. Despite its shorter atmospheric lifetime, CH_4 is a much more effective heat sink than CO_2 (United Nations Environment Programme, 2022). The Intergovernmental Panel on Climate Change (IPCC) states that 'the human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history'. Human activities since the Industrial Revolution have significantly increased the concentrations of these gases, leading to a rise in global temperatures and the adverse effects of climate change. The rapid industrialization and urbanization of many regions have further exacerbated the emission levels. The transportation sector, energy production, and industrial processes are significant contributors to CO_2 emissions. Additionally, the agricultural sector, including livestock and rice paddies, is a significant source of CH_4 and N_2O emissions. These emissions have far-reaching consequences, influencing weather patterns, sea levels, and biodiversity. The global aquaculture industry, although providing a sustainable alternative to wild fish capture, is a significant contributor to GHG emissions. Energy-intensive operations, land-use changes, feed production, and waste management all contribute to the carbon footprint of aquaculture (MacLeod et al., 2019).

1.1. GHG Emissions in the Context of Aquaculture Expansion

Aquaculture has experienced rapid growth in recent decades and has become a significant contributor to global food production. As the demand for seafood increases, aquaculture has become a more sustainable alternative to traditional livestock farming. However, the expansion of aquaculture also brings with it environmental challenges, including the emission of greenhouse gases (GHG), mainly nitrogen oxides (N_2O), methane (CH_4), and carbon dioxide (CO_2), from feed, agricultural energy consumption, fertilizers, and animal metabolism (MacLeod et al., 2019).

Anaerobic conditions in aquaculture ponds promote CH_4 production due to the breakdown of organic matter in oxygen-deprived environments (Pu et al., 2022). Moreover, N_2O emissions are associated with microbial activity in nitrogen-rich environments, such as those resulting from excessive fertilizer or feed application (Bano et al., 2024).

MacLeod et al. (2019) examined the greenhouse gas emissions of global aquaculture, a complex sector comprising various species farmed in diverse systems and environments. The analysis focuses on the main cultivated aquatic species groups, excluding marine plants. China is the world's largest producer and consumer of aquatic products, with its aquaculture sector playing a key role in ensuring global food security (FAO, 2020). The fisheries sector in Indonesia is experiencing significant growth in 2023, contributing around 3.2% to the country's gross domestic product (GDP) (Sulistijowati et al., 2023). Overall, East and South Asia are the world's largest producers of greenhouse gases, accounting for 90% of total production (Figure 2.1).

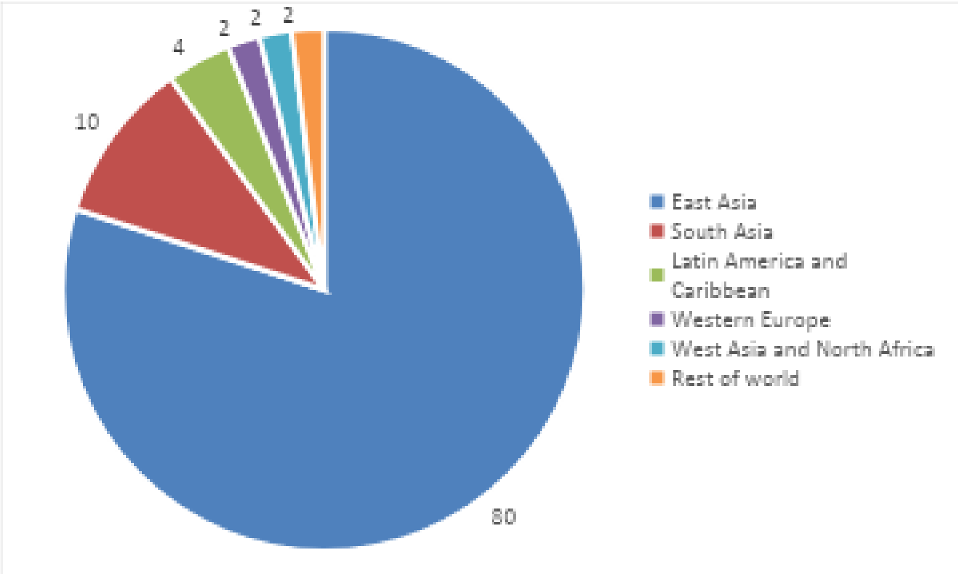

Figure 2.1. Percentage share of total GHG emissions by region (MacLeod et al., 2019)

When analysing the data for the various species, it becomes clear that the production of cyprinids accounts for the largest share of greenhouse gas emissions at 33%, followed by shrimp and prawn aquaculture at 18%. Intensive shrimp ponds, in particular, had higher productivity. Additionally, they have caused significant environmental impacts, particularly in coastal regions, as they produce substantial amounts of methane due to the anaerobic conditions that often prevail in the muddy bottoms of the ponds (Figure 2.2).

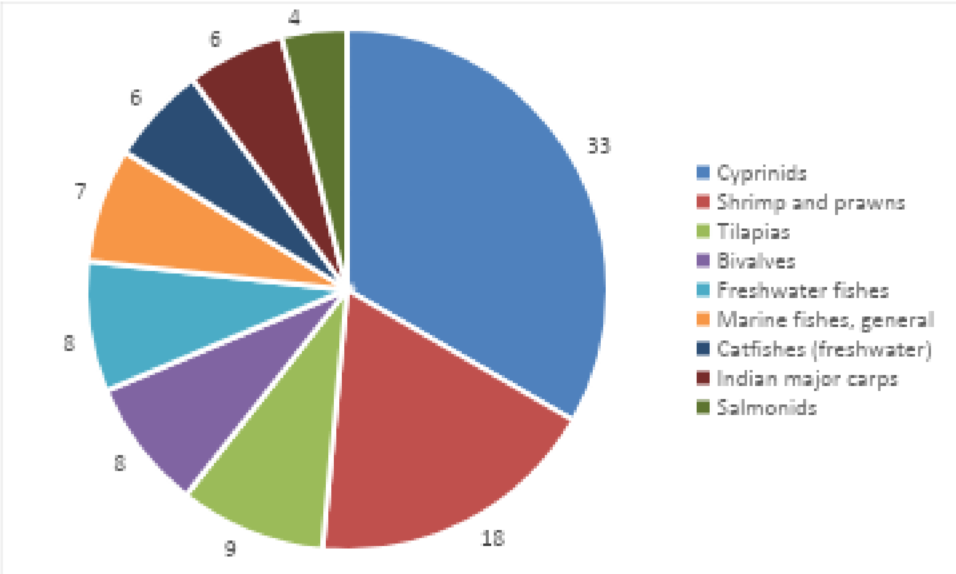

Figure 2.2. Percentage share of total GHG emission by species group (MacLeod et al., 2019)

After considering the various gases and their sources, aquatic feed production has the most significant influence, accounting for 55% of all greenhouse gases. Agricultural energy use and aquatic N_2O also have a significant share (Figure 2.3).

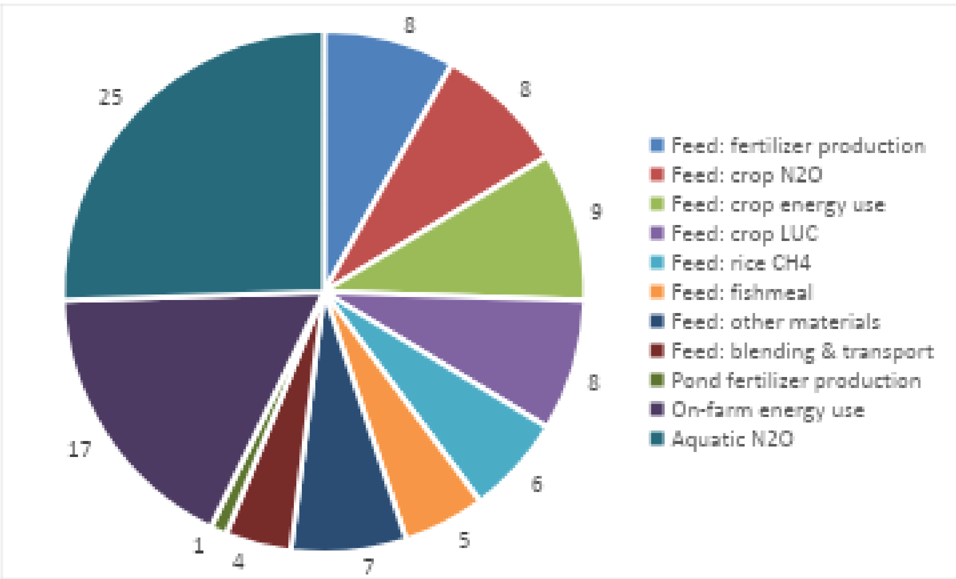

Figure 2.3. Percentage share of GHG emissions by source category (MacLeod et al., 2019)

1.2. Main Sources of Greenhouse Gases

N_2O is mainly produced by the microbial conversion of nitrogen in soils during crop cultivation, but also by the microbial conversion of nitrogenous compounds from feed and fertilizers in aquaculture ponds (MacLeod et al., 2019). The IPCC (2007) has reported increased concentrations of N_2O and CH_4 since industrial times, a concern since both gases, although present in lower concentrations than carbon dioxide (CO_2), have 298 (N_2O) and 25 (CH_4) times the global warming potential of CO_2 over 100 years. The rate of N_2O formation is determined by several physico-chemical factors such as temperature, salinity, and pH, which can change seasonally. Increased N_2O emissions from aquaculture have been reported in high-density fish farming systems, particularly in Asia, where aquaculture expansion is most significant (FAO, 2020). Studies indicate that even small-scale aquaculture can contribute to N_2O emissions comparable to those from agricultural activities (Rahman et al., 2022).

CO_2 is emitted by energy consumption before operation (mainly related to feed and fertilizer production), energy consumption during operation (e.g., water pumping, electricity consumption, use of other fuels), and distribution and processing after operation. CO_2 emissions also result from changes in above- and below-ground carbon stocks caused by land use and land use change (LUC) (conversion of grassland to cropland). CH_4, which is mainly generated by the anaerobic decomposition of organic matter in flooded rice cultivation, can also be generated by the management of fish farm waste (MacLeod, 2019). Fish farms generate organic waste, including uneaten feed, fish excreta, and other by-products. When these materials decompose in an anaerobic environment, such as in sediments or poorly managed waste lagoons, methane (CH_4) is released (Pu et al., 2022).

2. Energy Consumption and Sustainability

The carbon footprint of aquaculture operations is directly related to the energy sources used. In many regions, aquaculture operations rely on electricity from fossil fuels, which releases significant amounts of CO_2 into the atmosphere. The carbon intensity of electricity generation varies depending on the energy mix of a particular region. In areas where electricity is predominantly generated from coal, oil, or natural gas, the carbon footprint of aquaculture operations can be significant. The use of fossil fuels for energy production in aquaculture operations contributes directly to GHG emissions. Carbon emissions from energy use in aquaculture can be significant, especially for large, energy-intensive operations (Li et al., 2024).

2.1. Energy Sources and Their Environmental Impact

Despite the importance of aquaculture for food production, concerns have been raised about its expansion (Naylor et al., 2000). Some of the environmental issues associated with aquaculture are feed production and the release of nutrient-rich effluents into the environment due to animal metabolism (Thomas et al., 2021). The environmental sustainability of products, processes, or services is often assessed using the Life Cycle Assessment (LCA), which is a methodology defined by standards ISO 14040 and 14044 (ISO, 2006a, 2006b) to quantify the potential environmental impact on ecosystems, human health, and natural resources caused by products and systems throughout their entire life cycle (Cucurachi et al., 2019). Energy use in aquaculture is crucial for maintaining the conditions necessary for the growth of farmed species, including water circulation, aeration, temperature regulation, and feeding (Table 2.1).

Table 2.1. Energy use in different stages of aquaculture operations

Aquaculture operations	Energy requirements
Hatcheries and nurseries	Temperature control, lighting, and water circulation.
Pond and tank systems	Aeration, pumping, and filtration
Recirculating aquaculture systems (RAS)	water treatment and temperature regulation
Cage and offshore systems	Boat transport, feeding systems, and harvesting
Feed production and processing	Energy-intensive ingredient sourcing, manufacturing, and transportation

However, these energy demands, especially when powered by fossil fuels, contribute to the carbon emissions that exacerbate global warming. As the industry continues to expand, understanding and mitigating the energy-related environmental impacts of aquaculture are crucial for ensuring its long-term sustainability. To achieve sustainability in aquaculture, it is crucial to balance environmental impacts with energy consumption. Integrating renewable energy sources into aquaculture operations can significantly reduce greenhouse gas emissions (Table 2.2).

Table 2.2. Primary energy sources in aquaculture

Energy sources	Used
Fossil fuels (diesel, coal, natural gas)	Generators, transport, and production facilities
Electricity	Primarily from non-renewable sources, powering water pumps, aeration systems, and refrigeration

Selection of the farming system and, ultimately, selection of species with lower feed and water quality requirements can decrease both environmental impact and energy use. Energy costs of production not only involve sustainability issues related to ecosystem resource efficiency and non-renewable resource depletion, but also the potential cost to future societies through environmental changes resulting from pollution and global climate change (FAO, 2022; Parker et al., 2018).

2.2. Energy Sources and Their Environmental Impact

Aquaculture is a highly energy-intensive industry, where various operations require substantial amounts of energy to create optimal conditions for the species being farmed. These operations include water circulation, aeration, temperature control, and feeding systems, all of which are necessary to promote the growth and health of aquatic organisms. The energy consumption associated with these activities varies depending on the scale of the operation and the species being farmed.

1. Water circulation and aeration. Maintaining adequate oxygen levels in aquaculture facilities is critical to the health and survival of fish and shellfish. Aeration systems are commonly used to increase oxygen levels in the water, especially in intensive aquaculture facilities where large numbers of organisms are grown in a confined space. These systems require substantial amounts of energy, particularly in large-scale operations. Water circulation systems are also used to ensure that oxygen, nutrients, and waste products are evenly distributed throughout the water, further increasing energy requirements (Tacon & Metian, 2009).

2. Temperature control. Temperature plays an important role in the growth and metabolism of aquatic organisms. In some regions, aquaculture operations must regulate water temperatures to create optimal conditions for the species being farmed. This is particularly true in colder climates or when breeding tropical species in temperate regions. Temperature regulation often requires energy-intensive systems such as heaters, coolers, and heat exchangers. These systems are crucial for maintaining the ideal temperature range for water to remain in for growth and reproduction, but they also contribute to high energy consumption (Boyd & McNevin, 2015).

3. Feeding systems. Automated feeding systems are commonly used in aquaculture to optimise feeding efficiency and minimise waste. These systems are powered by electricity and are used to distribute feed to large numbers of fish or shellfish in a controlled manner. While automated feeding systems can improve feed conversion and overall productivity in aquaculture operations, they also contribute to the operation's energy requirements (Matulić et al., 2020).

3. Land Use Change and Habitat Conversion

As global demand for fish and seafood continues to rise, reconciling the growth of aquaculture with environmental sustainability is a major challenge. The rapid expansion of aquaculture has led to significant changes in land use and habitat conversion, particularly affecting ecologically valuable ecosystems such as mangroves, wetlands, and coastal areas. These changes contribute to biodiversity loss, carbon emissions, and overall ecosystem degradation, raising concerns about the long-term viability of aquaculture (Barbier et al., 2011).

Mangrove Destruction and Carbon Emissions

The loss or degradation of habitats, in particular of coastal habitats such as mangrove systems and other wetlands (seagrass meadows, saltmarshes, coastal lagoons, estuaries) is one of significant adverse impacts of aquaculture (Wu, 1995; Dev, 1998; Naylor et al., 2000; Páez-Osuna, 2001; Ruiz et al., 2001; Pérez et al., 2008). Mangrove forests, which are crucial to coastal ecosystems, are the primary source of organic matter in these environments (Tidwell & Allan, 2001). They also serve as critical nursery habitats for numerous economically important aquatic species, as well as nesting and resting areas for a variety of other groups (Paez-Osuna, 2005). In addition, mangroves contribute to coastal protection by retaining sediments, pollutants, nitrogen, and carbon and reducing erosion (Alongi, 2002; Walters et al., 2008). However, the rate of mangrove deforestation is estimated at 1–2% per year, with shrimp and fish aquaculture being the leading cause of the loss of millions of hectares of mangrove forests in countries such as Thailand, Indonesia, Ecuador, and Madagascar (Naylor et al., 2000; Harper et al., 2007). Studies conducted in marine cage farms on the Mediterranean coastline have reported the destruction/degradation of Posidonia oceanica meadows as a consequence of high organic and nutrient loading from fish farming activities. Conversion of mangrove forests into shrimp farms (Dev, 1998; Choo, 2001; Páez-Osuna, 2001) has mainly caused the loss of feeding, nursery, shelter and spawning grounds for a wide variety of marine and terrestrial animals (Ruiz et al., 2001; Pérez et al., 2008), and the loss of natural protection against floods, storms and hurricanes (Dev, 1998; Choo, 2001; Páez-Osuna, 2001).

The destruction of mangroves for aquaculture not only robs them of their ability to store carbon, but also releases stored carbon from the soil into the atmosphere. According to Alongi (2015), the conversion of mangrove forests into shrimp farms leads to a significant increase in carbon dioxide (CO_2) emissions. As mangroves are among the most carbon-dense ecosystems on the planet, storing up to five times more carbon per hectare than tropical forests, their loss is a critical environmental issue (Barbier et al., 2011). In addition to carbon loss, the degradation of coastal wetlands increases vulnerability to erosion and flooding, weakens coastal resilience, and makes local communities more vulnerable to the impacts of climate change (Barbier et al., 2011).

Conversion of Wetlands and Agricultural Land

The expansion of inland aquaculture has also led to significant changes in land use, particularly through the conversion of agricultural land and wetlands to aquaculture operations. Driven by the economic advantages of aquaculture, which often yields higher financial returns than traditional agriculture, this conversion introduces several environmental problems (Ahmed & Thompson, 2019). One major issue is the destruction of ecosystems, as wetlands, which are important for water filtration, flood control, and biodiversity, are drained to make way for aquaculture ponds. This leads to a loss of biodiversity and impairs the landscape's ability to cope with environmental change.

Rahman et al. (2022) demonstrate that the conversion of agricultural land to aquaculture areas results in significant and often irreversible ecological damage, underscoring the need for sustainable land use practices. In addition, intensive aquaculture can lead to the accumulation of organic waste, chemicals, and excess nutrients in soil and water, resulting in eutrophication. This process, characterised by excessive amounts of nutrients, leads to algal blooms and oxygen depletion and has severe impacts on aquatic ecosystems (Boyd et al., 2020).

Habitat Fragmentation and Loss of Biodiversity

The expansion of aquaculture has contributed to habitat fragmentation, which disrupts ecological connectivity and hinders the ability of species to migrate, reproduce, and access food resources. This fragmentation can lead to a decline in populations and a loss of biodiversity. The introduction of alien species for breeding purposes exacerbates these effects as they compete with or decimate native species, further destabilising ecosystems (Chavez et al., 2020).

Recent studies show the profound impact of habitat fragmentation on biodiversity (Marrone et al., 2023). The conversion of agricultural land to aquaculture areas has led to permanent ecological changes, underscoring the importance of adopting sustainable practices during such transitions (Rahman et al., 2022). Habitat destruction leads to a reduction in population sizes and fragmentation of species' ranges, disrupting the movement of individuals between habitat patches and reducing their chances of survival (Haddad et al., 2015).

4. Feed Production and Resource Use

The production of feed for aquaculture is a crucial aspect of the sector, but it has a significant environmental impact. The cultivation of feed ingredients, such as fishmeal and plant-based ingredients, requires significant natural resources, including land, water, and energy. This contributes to greenhouse gas emissions and environmental degradation. It is estimated that up to 90% of greenhouse gas emissions from fish farms are attributable to the production of aquaculture feed (FAO, 2022). As the demand for aquaculture products increases, sustainable practices for feed production are crucial to minimise the environmental impact and ensure the long-term sustainability of the industry.

4.1. Feed for Aquaculture and Alternative Sources

Various types of feed are used in aquaculture to meet the nutritional requirements of farmed fish and seafood, ensuring the growth and health of the animals. Traditionally, fishmeal has been the primary component of aquaculture feed. Fishmeal is derived from small pelagic fish such as anchovies and sardines. However, due to concerns about overfishing, resource depletion, and the sustainability of marine ecosystems, interest in alternative feed sources has increased (Tacon & Metian, 2009).

In response to these challenges, the industry is exploring alternative feed ingredients. Plant-based proteins, such as those derived from soy, corn, and wheat, are among the most commonly investigated options. These ingredients are considered potential replacements for fishmeal and are utilized in aquaculture feed to reduce dependence on marine resources (Duarte et al., 2020; O'Flynn et al., 2021). Additionally, insect-based proteins, such as those derived from soldier flies and mealworms, have recently emerged as a promising alternative. These insect proteins can be cultivated using organic waste, offering a potential solution to reduce the need for land conversion and minimize ecological impact (Freda et al., 2022).

Overall, the search for alternative feed ingredients reflects the growing awareness of the need to reconcile fish farming and sustainability. This conversion of feed sources aims to reduce dependence on marine resources while maintaining the nutritional quality of feed for farmed species.

4.2. Environmental Impact of Feed Production in Aquaculture

Environmental Impact of Plant-based Feedstuffs

Replacing fishmeal with plant-based ingredients such as soy and maize reduces pressure on marine ecosystems, but creates new environmental problems (Tacon & Metian, 2009). The increasing demand for these alternatives has led to large-scale land conversion, particularly in tropical regions, to meet the growing demand for agricultural resources (Fargione et al., 2023). This change in land use has led to significant environmental impacts, including deforestation, habitat loss, and a decline in biodiversity. Tropical rainforests are particularly affected as large areas are cleared to grow crops such as soy and maize, which are important for animal feed production (Fargione et al., 2023).

Impacts on Climate Change and Greenhouse Gas Emissions

Apart from land conversion, the environmental impacts of crop-based feed production also exacerbate climate change through the emission of greenhouse gases. The conversion of forests into agricultural land for animal feed production contributes significantly to carbon dioxide (CO_2) emissions. This occurs not only directly through the loss of carbon storage in the forests, but also through the energy-intensive processes involved in clearing and transportation (Soussana et al., 2021). Furthermore, the use of synthetic fertilizers and pesticides in crop cultivation results in the release of nitrous oxide (N_2O), a potent greenhouse gas that exacerbates global warming (Pardoe et al., 2022). These emissions destabilise both the local and regional climate, making the aquaculture industry more vulnerable to climate-related challenges.

Land Degradation, Water Consumption, and Agricultural Biodiversity

As a key component of many aquaculture feeds, soy has become a significant contributor to various environmental problems, particularly in terms of soil degradation, excessive water consumption, and loss of agricultural biodiversity (Magrin et al., 2020). The rapid expansion of soy monocultures has led to concerns about soil erosion, nutrient runoff, and increased susceptibility to pests and diseases. These problems often require the increased use of chemical fertilizers and pesticides, which further exacerbate environmental damage. Such practices contribute to water pollution and eutrophication, damaging both freshwater and marine ecosystems (Pardoe et al., 2022). In addition, the destruction of valuable ecosystems, such as wetlands and forests, for agricultural expansion disrupts local carbon cycles, reduces the landscape's ability to adapt to climate change, and increases vulnerability to extreme weather events, including floods and droughts (Fargione et al., 2023).

Carbon Footprint and Energy Consumption

In addition to land-use changes, large-scale agricultural processes for feed production are a significant source of greenhouse gas emissions (Soussana et al., 2021). The energy-intensive processes associated with land conversion, as well as the high demand for fertilizers and transportation, contribute to a significant carbon footprint. In addition, the processing of plant materials into fish feed often involves energy-intensive processes, which exacerbate the environmental impact. This problem is particularly severe when fossil fuels are incorporated into production processes. As a result, these environmental challenges underscore concerns about the long-term sustainability of plant-based feed alternatives in the face of global climate change.

4.3. Feed Selection and Nutrition in Aquaculture

Factors Influencing the Choice of Feed

The choice of feed for farmed fish and crustaceans depends on several factors, including the feeding habits of the species (herbivores, omnivores, or carnivores), the market value of the species, and the farming system used. The rearing system, whether it is an earthen pond, an enclosure, a raceway, or a cage, also affects the choice of feed. Intensive systems require specially formulated feeds to optimise growth and feed conversion rate (FCR), while extensive systems can rely more on naturally occurring food organisms (Tacon et al., 2013).

Economic and Environmental Considerations in Feed Selection

Another key factor is the availability of commercially formulated feeds. If these are unavailable or unsuitable, farmers may turn to home-produced feeds produced from local ingredients such as low-grade fish or agricultural by-products. The farmer's financial resources, including the costs of feed, storage, and labour, play a crucial role in this decision-making process (Tacon et al., 2013). Poor feeding strategies, such as overfeeding, can lead to nutrient wastage and environmental pollution. Therefore, feed management must also strike a balance between economic efficiency and environmental sustainability (White, 2013).

Feed Quality and Feed Efficiency

An important concern in aquaculture is to meet the nutritional requirements of fish through appropriate feed rationing that optimises growth and FCR. The energy and nutrient requirements of fish species can vary daily, seasonally, and from individual to individual. Unbalanced diets, underfeeding, or overfeeding can reduce production efficiency and contribute to environmental degradation, especially in cage farming (Bureau et al., 2006; Thorpe & Cho, 1995). To minimise wastage and achieve both economic and environmental sustainability, effective feed management strategies are essential (Talbot, Corneillie & Korsøen, 1999; Cho & Bureau, 1998).

Overfishing

The exploitation of wild resources and biodiversity for aquaculture feed production, as well as the supply of seed and broodstock, can cause significant damage to aquatic ecosystems (Dev, 1998; Choo, 2001; Páez-Osuna, 2001). Wild fish species of low commercial value, such as Japanese anchovy and chub mackerel, are often used as feed for carnivorous fish or as supplementary feed for species such as shrimp, tilapia, and milkfish. This practice puts additional pressure on already overfished wild fish stocks. The removal of wild-caught fish such as eel, grouper, yellowtail, and tuna further contributes to the depletion of natural populations.

The collection of wild-caught shrimp and shellfish seed is especially harmful, as it not only threatens the target species but also kills non-target organisms, including other shrimp species, macrozooplankton, and juvenile fish and shellfish. This disruption of the food web affects a wide range of organisms, including waterfowl, reptiles, and mammals, resulting in increased mortality and reduced breeding success (Choo, 2001). Additionally, the removal of wild species can lead to genetic degradation of native populations and destruction of natural habitats, resulting in further disruption of the aquatic ecosystem (Dev, 1998). This problem is significant for heavily fished species and those with low reproductive capacity. As long as the production of captive broodstock remains costly, the purchase of wild spawners is likely to continue, causing further environmental damage (Nash, 2005).

5. Pollution and Residual Substances

Aquaculture facilities can generate significant amounts of wastes/effluents containing a variety of substances, such as particulate material (mainly from uneaten feed and faeces), dissolved metabolic products (from excretion *via* gills and kidneys) and various forms of chemicals (e.g., therapeutics, fertilizers, heavy metals), with undesirable consequences for the environment (Wu, 1995; Dev, 1998; Páez-Osuna, 2001; Read and Fernandes, 2003). The environmental impacts resulting from particulate and dissolved organic and inorganic material (Table 3) are significant as these compounds enter the environment directly and affect both the water column and sediment (Dalsgaard & Krause-Jensen, 2006; Holmer et al., 2007). The extent of these impacts depends primarily on the farm's location, animal species, crop type, stocking density, feed digestibility, and other husbandry factors, such as feeding practices and disease status (Wu, 1995).

Table 2.3. Drivers, pressures, states, impacts, and responses for a hypothetical aquaculture development (Serpa & Duarte, 2008)

Driver	Pressure	State	Impact	Response
Fish farming	Increased nutrient fluxes	Increased nutrient and organic matter concentrations	Increased phytoplankton biomass/eutrophication	Seaweeds' production to remove excess nutrients
	Increased organic matter fluxes, decreased oxygen levels and oxygen	Decreased oxygen levels. Accumulation of organic matter In the sediments	Higher mortality of benthic organisms/decreased benthic diversity	Bottom aeration
	Increased drag forces	Reduced flow-through and increased residence time	Increased sediment deposition	Reallocation to areas of more intense hydrodynamics

	Release of xenobiotics	Bioconcentration	Increased mortality of non-target species	Less intensive farming to reduce disease propagation

The meteorological (e.g., wind patterns), hydrographical (e.g., bathymetry, currents, tidal regime, wave action, sedimentation rates), and geomorphological characteristics of aquaculture sites (Nordvarg & Hakanson, 2002; Kalantzi & Karakassis, 2006) strongly influence the fate of any waste released into the water column.

Effluents from intensive production systems, with a considerable feed input, typically have greater adverse impacts than effluents from semi-intensive or extensive systems with little or no feed addition (Kautsky et al., 2000; PáezOsuna, 2001).

Aquaculture waste, including uneaten feed, fish excreta, and chemical residues, has significant environmental impacts. Excess nutrients, such as nitrogen and phosphorus, contribute to water pollution and eutrophication, resulting in oxygen depletion and the formation of harmful algal blooms. The use of chemicals in aquaculture can lead to antibiotic resistance and ecosystem disruption, while habitat degradation, such as mangrove deforestation, poses a threat to biodiversity. Addressing these challenges requires sustainable practices like improved waste management and eco-friendly farming techniques to minimise the adverse effects of aquaculture on the environment.

5.1. Nutrient Discharges

Waste from aquaculture, particularly uneaten feed and fish excreta, introduces high levels of nitrogen and phosphorus into surrounding waters. This nutrient enrichment can lead to eutrophication, characterised by excessive algal blooms that deplete oxygen levels and harm aquatic life.

Inputs of inorganic compounds (e.g., ammonia, nitrates, nitrites and phosphates) through organic matter breakdown, animal excretion and pond fertilisation may also have potentially hazardous effects on the surrounding environment (Wu, 1995; Dev, 1998; Tovar et al., 2000; Páez-Osuna, 2001; Pearson & Black, 2001; Read & Fernandes, 2003; Biao & Kaijin, 2007; Pérez et al., 2008). Most of the undesirable ecological consequences related to excessive nutrient availability from aquaculture discharges are associated with eutrophication, including, for example, hypernutrification and the depletion of dissolved oxygen, which cause deterioration in water quality (Tovar et al., 2000a; Read & Fernandes, 2003). Nutrient loadings also contribute to the pool of plant nutrients in aquatic systems, stimulating the growth of primary producers (Read & Fernandes, 2003; Biao & Kaijin, 2007) and even changing the structure and composition of these key communities.

Should nutrient enrichment coincide with particular physical conditions and other poorly understood factors, there may be a growth of toxic phytoplankton species, leading to the formation of Harmful Algal Blooms, HAB (Biao & Kaijin, 2007). For example, reports of HAB of *Chattonella marina*, presumably caused by effluent discharges from shrimp farms, were documented along the north of the Yellow Sea in 1993 and 1995 (Biao & Kaijin, 2007). Toxic phytoplankton blooms may produce different types of toxins (e.g., DSP – diarrheic shellfish poisoning, PSP – paralytic shellfish poisoning, ASD – amnesiac shellfish disease), that often cause shellfish poisoning and the mortality of benthic fauna and wild/farmed fish, thereby threatening the economic viability of aquaculture activities (Pearson & Black, 2001; Read & Fernandes, 2003; Gyllenhamman & Hakanson, 2005). Although the potential for eutrophication appears unlikely in marine cage farming due to the dilution effect of seawater (Wu, 1995; Pearson & Black, 2001), the possibility of localised eutrophication in areas of poor flushing cannot be excluded (Wu, 1995; Pearson & Black, 2001). In terms of restricted exchange areas, such as coastal lagoons and estuaries, excessive nutrient availability can affect ecosystem productivity and, in some cases, negatively impact aquaculture activity itself (Dev, 1998; Páez-Osuna, 2001b).

5.2. Impacts of Antibiotics and Chemical Use

The use of antibiotics and other chemicals in aquaculture to prevent disease can result in residues entering the environment. These substances may disrupt local ecosystems and contribute to the development of antibiotic-resistant bacteria. Research indicates that pollutants from aquaculture are dispersed quickly in rivers. However, effluent water from fish farms contributes to less than 1% of total suspended solids, biological oxygen demand, and phosphorus discharged into the environment. Chemicals used in aquaculture operations may be categorised as: 1) feed additives (e.g., vitamins, pigments, minerals, and hormones), 2) disinfectants (e.g., bleach, malachite green) and pesticides (e.g., molluscicides and piscicides), 3) liming materials, 4) metals (e.g., antifoulants) and 5) veterinary medicines, including antibiotics, anaesthetics, parasiticides, and vaccines (Read & Fernandes, 2003) used to control external and internal parasites or microbial infections (Costello et al., 2001).

The use of antibiotics in aquaculture has several adverse environmental effects. The widespread use of antibiotics in aquaculture can lead to the development of antibiotic-resistant bacteria, which can transfer their resistance genes to other bacteria, including those that cause diseases in humans and other animals (Okocha et. al., 2018). Antibiotics can have toxic effects on microorganism communities in aquatic environments, including algal communities, which are crucial for the health of aquatic ecosystems (Li et al., 2024). Additionally, antibiotics and their byproducts can persist in natural environments due to their difficult biodegradation, accumulating in sediments, aquatic surfaces, and groundwater, leading to long-term environmental contamination. The presence of antibiotics in aquatic environments can lead to severe changes in the composition and structure of bacterial communities, thereby affecting the overall health and biodiversity of aquatic ecosystems (Luthman et al., 2024). Furthermore, the use of antibiotics in aquaculture can lead to the presence of residual antibiotics in fish and other aquaculture products, posing health risks to humans who consume these products. The indiscriminate use of antibiotics in aquaculture can also lead to the disruption of normal intestinal flora in aquatic animals, resulting in negative impacts on their health and growth. Moreover, the accumulation of antibiotics in the environment can lead to the development of antibiotic-resistant pathogens, which can spread to other ecosystems and pose a threat to both aquatic and terrestrial life (Farias et al., 2024).

Other biological products, such as organic matter decomposers (e.g., bacteria and enzyme preparations), are also used (Gräslund & Bengtsson, 2001). The application of these chemicals is mainly dependent on the culture system. For instance, while semi-intensive shrimp farms require a minimal use of chemicals, mostly fertilizers and liming materials (Boyd & Massaut, 1999; Choo, 2001; Gräslund & Bengtsson, 2001), as shrimp production is intensified, management becomes more problematic, and the number and diversity of chemical compounds essentially increases (Gräslund & Bengtsson, 2001).

Intensive pond culture also requires a higher diversity of chemicals when compared to cage systems, which mainly use disinfectants, antifoulants, and veterinary medicines (Kelly & Elberizon, 2001; Read & Fernandes, 2003). The main environmental risks associated with the use of chemical compounds relate to: 1) deterioration of water quality, 2) interference on biogeochemical processes, 3) direct toxicity to wild fauna and flora, 4) development of resistance by pathogenic organisms, and 5) reduction of the prophylactic efficiency of therapeutants (Costello et al., 2001). The improper use of chemical compounds may also compromise the safety of aquaculture products, posing a threat to human health (Choo, 2001; Islam et al., 2004).

Summary

Aquaculture plays a vital role in global food security; however, its rapid expansion has raised significant environmental concerns, particularly in the context of climate change. The industry is a significant source of greenhouse gas emissions, habitat destruction, and resource depletion. Carbon dioxide, methane, and nitrous oxide are released through energy-intensive operations, feed production, and waste management. Many aquaculture facilities rely on fossil fuels for electricity, thereby increasing carbon emissions, while anaerobic conditions in fish ponds contribute to the release of methane. Additionally, nitrous oxide emissions result from nitrogen-rich environments created by excess feed and fertilizers. The rapid expansion of aquaculture has also led to widespread land-use changes, particularly in coastal and wetland ecosystems. Mangroves and other vital habitats have been cleared to make space for shrimp farms and fish ponds, leading to biodiversity loss, coastal erosion, and reduced carbon sequestration. Feed production is one of the most significant contributors to aquaculture’s environmental footprint, accounting for the majority of emissions. Traditional fishmeal-based feeds put pressure on marine resources, while plant-based alternatives, such as soy, contribute to deforestation, land degradation, and water overuse. Insect-based proteins and other novel feed sources offer potential solutions; however, their large-scale adoption remains limited due to economic and logistical challenges. Another significant issue is waste generation, as uneaten feed, fish excreta, and chemical residues contribute to water pollution, eutrophication, and harmful algal blooms, leading to oxygen depletion and ecosystem imbalances. The use of antibiotics in aquaculture raises concerns about antibiotic resistance, which can impact both aquatic environments and human health. Addressing these challenges requires a shift towards sustainable practices, including integrating renewable energy, optimising feed efficiency, adopting responsible land-use strategies, and implementing effective waste management solutions. As global seafood demand continues to rise, balancing aquaculture growth with environmental responsibility is crucial to ensure long-term industry sustainability and minimise its ecological impact.

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Chapter 3. Global Warming and Breeding, Biotechnology in Aquaculture

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Introduction

Aquatic ecosystems, essential to global biodiversity and human livelihoods, are undergoing unprecedented changes due to global warming. Rising temperatures, driven by anthropogenic climate change, are disrupting breeding cycles, survival rates, and the genetic integrity of aquatic species. Simultaneously, the field of aquaculture is navigating these challenges through innovative biotechnological solutions. With the world's reliance on aquatic resources increasing to meet food security demands, the integration of advanced breeding technologies, including selective breeding, genomic selection, and CRISPR–Cas9 gene editing, offers transformative potential to address the dual crises of climate change and sustainable aquaculture.

This chapter explores the complex interplay between environmental changes and biotechnological advancements in aquaculture. It begins by examining how global warming affects the breeding cycles and survival dynamics of aquatic species, resulting in significant shifts in population structures and ecosystem functions. The focus then shifts to groundbreaking biotechnological solutions, such as selective breeding and genomic selection, which are enhancing the resilience and productivity of aquaculture species. Furthermore, the revolutionary CRISPR–Cas9 gene-editing technology is discussed, highlighting its applications in improving disease resistance, growth rates, and environmental adaptability in various fish species. Finally, the ethical, environmental, and regulatory considerations surrounding these technologies are examined, emphasising the need for sustainable and responsible innovation in aquaculture.

The implications of these discussions are far-reaching, influencing not only the future of aquaculture but also global efforts to mitigate biodiversity loss and the impacts of climate change. This introduction sets the stage for a comprehensive analysis of the challenges and opportunities presented by integrating biotechnology into aquaculture in the context of global warming.

1. Climate Change and Species Reproduction

1.1. Changes in Breeding Cycles

Global warming, driven by human-induced climate change, is having a profound impact on ecosystems around the world, including aquatic environments. One of the most significant areas affected by rising temperatures is the breeding of aquatic species. Changes in water temperature are altering breeding cycles, spawning times, growth rates, and the survival rates of offspring, leading to shifts in the structure and functioning of aquatic populations. This literature review aims to explore how environmental changes are influencing aquatic species, with a focus on alterations in breeding cycles and genetic adaptation.

Changes in Breeding Cycles. Rising water temperatures due to global warming are one of the primary drivers of changes in the reproductive behaviour of aquatic species. Many species rely on specific temperature cues to initiate breeding. With increasing temperatures, the timing of breeding events has shifted, and these shifts can lead to mismatches between species and their habitats.

Spawning Times. Studies have shown that many aquatic species are breeding earlier in the year due to warmer water temperatures. For instance, fish species such as the Atlantic cod (*Gadus morhua*) and the European perch (*Perca fluviatilis*) have been observed to spawn earlier in the season in response to increased water temperatures (Tompkins et al., 2017). While earlier spawning may initially seem beneficial, it often leads to a mismatch with the availability of food resources for larvae, as phytoplankton, a primary food source for many young fish, may not be available at the same time (Durant et al., 2007). This could result in decreased survival rates of offspring, which would further impact population dynamics.

Moreover, earlier spawning does not necessarily guarantee success, as species may spawn before optimal conditions for larval survival are met. The mismatch in timing can lead to a reduced number of viable offspring, potentially leading to long-term population declines (O'Reilly et al., 2008).

Growth Rates and Metabolic Effects. The increase in water temperature also influences the metabolic rates of aquatic species. Warmer temperatures typically accelerate the growth of many species by increasing metabolic rates (Angilletta et al., 2004). However, this increase in growth rate may not always be beneficial. Species that grow too quickly in warmer waters may not develop the necessary size or strength to survive into adulthood, resulting in weaker individuals with lower chances of successful reproduction (Heath et al., 2014). Additionally, faster growth does not always correlate with an increase in reproductive success, as the species may face a mismatch in the timing of their developmental milestones and environmental conditions.

Survival Rates of Larvae. The early life stages of aquatic species are often the most vulnerable to environmental changes, and rising water temperatures can further exacerbate these vulnerabilities. Elevated temperatures can reduce the oxygen levels in the water, affecting the survival rates of larvae, which require high oxygen concentrations for proper development (Pörtner et al., 2014).

Furthermore, higher temperatures may stress juvenile organisms, leaving them less capable of handling other environmental challenges, such as predation or food scarcity (Walther et al., 2002).

1.2. Genetic Adaptation to Climate Change

While environmental changes pose challenges for aquatic species, some have the potential to adapt genetically to these changing conditions. Genetic adaptation involves changes in the genetic makeup of populations over time that allow species to cope with environmental stressors, including higher temperatures.

Adaptation to Temperature Changes. Research has suggested that specific species have shown some degree of genetic adaptation to rising temperatures. For example, studies on the Atlantic cod have found evidence of local adaptation to varying thermal conditions in different geographic areas (Jorgensen et al., 2017). Some populations of cod living in warmer waters have developed genetic traits that enable them to spawn successfully at higher temperatures. Similarly, some fish species may exhibit shifts in their reproductive timing or physiological tolerance, adapting to warmer environments over multiple generations (Lynch et al., 2014).

However, the ability of species to adapt genetically is limited by factors such as genetic diversity and the speed at which environmental changes occur. Species with low genetic diversity or those in rapidly warming habitats may struggle to adapt quickly enough to avoid population declines (Fischer et al., 2014). Additionally, the process of genetic adaptation is slow, and the rate of warming may exceed the ability of some species to adapt genetically in a timely manner.

Reduced Reproductive Success and Population Decline. While some species may successfully adapt to warming temperatures, others may face challenges that reduce their reproductive success or lead to population declines. For instance, species with specialised breeding requirements, such as those that rely on particular temperature ranges for spawning, may struggle to cope with the rapid temperature shifts caused by global warming (Parmesan, 2006). In such cases, reproductive success may decrease, and populations may experience a decline in numbers or even local extinctions.

Species that do not adapt genetically to rising temperatures may be unable to reproduce successfully in their native habitats, leading to a loss of genetic diversity and further reducing their chances of survival in the face of climate change (Chevin et al., 2010).

The impact of global warming on aquatic species breeding is multifaceted, involving shifts in breeding cycles, changes in growth rates, and alterations in the survival rates of offspring. Rising temperatures have led to earlier spawning in many species, but this may cause a mismatch with food availability and optimal environmental conditions, resulting in lower survival rates for larvae. While some species may be able to adapt to changing temperatures genetically, the rate of environmental change may exceed their ability to do so, leading to reduced reproductive success and potential population declines. Further research is necessary to understand the long-term consequences of these changes on aquatic ecosystems and to develop strategies for mitigating the effects of climate change on these species.

2. Advanced Breeding Methods

2.1. Selective Breeding

Aquaculture is a rapidly growing sector that contributes significantly to global food security. As the climate continues to change, aquaculture faces increasing challenges, such as rising temperatures and more frequent extreme weather events. To address these challenges, biotechnological advancements, particularly in selective breeding and genomic selection, are being increasingly applied to develop aquaculture species that are more resilient to climate-related stresses.

Selective breeding has been a cornerstone of aquaculture for decades, enhancing the productivity and resilience of farmed species. The process involves selecting individuals with desirable traits for reproduction, thus gradually improving the genetic composition of populations. Traditional selective breeding in aquaculture has focused on traits such as growth rate, disease resistance, and feed conversion efficiency. With climate change intensifying environmental stressors, there is a growing emphasis on breeding for traits that confer greater resilience to elevated water temperatures and other climate-related challenges.

Research has shown that selective breeding can help aquaculture species, such as fish and shellfish, adapt to warmer environments. For example, studies on Atlantic salmon have shown that selective breeding can enhance heat tolerance, potentially enabling farmed populations to survive in warmer waters resulting from climate change (Gjøen et al., 2018). Additionally, selective breeding programs are increasingly focusing on traits like disease resistance and the ability to withstand hypoxic conditions, which are likely to become more prevalent as water temperatures rise (Houston et al., 2018).

Selective breeding for climate resilience also includes enhancing behavioural traits. For instance, fish that exhibit greater tolerance to stressors such as crowding and handling can better withstand the harsher conditions created by climate change (Huntingford et al., 2020). These breeding programs aim to ensure that aquaculture species can continue to thrive under a changing climate, contributing to long-term sustainability.

2.2. Genomic Selection

The use of modern biotechnology to enhance the production of aquatic species holds great potential not only to meet demand but also to improve aquaculture. Genetic modification and biotechnology also hold tremendous potential to improve the quality and quantity of fish reared in aquaculture. There is a growing demand for aquaculture; biotechnology can help to meet this demand. As with all biotech-enhanced foods, aquaculture products will be strictly regulated before they are approved for market. Biotech aquaculture also offers environmental benefits. When appropriately integrated with other technologies for the production of food, agricultural products, and services, biotechnology can significantly assist in meeting the needs of an expanding and increasingly urbanized population in the next millennium. Successful development and application of biotechnology are possible only when a broad research and knowledge base in biology, variation, breeding, agronomy, physiology, pathology, biochemistry, and genetics of the manipulated organism exists. The benefits offered by new technologies cannot be fulfilled without a continued commitment to basic research. Biotechnological programs must be fully integrated into a research background and cannot be taken out of context if they are to succeed.

Figure 3.1 shows the role of biotechnology in enhancing fish production.

Genomic selection, which uses genomic tools to identify and propagate desirable traits, represents a significant leap forward in aquaculture breeding. This technique involves associating genetic markers with traits of interest, allowing for more efficient selection. Genomic selection can accelerate breeding programs by enabling breeders to identify individuals with the best genetic potential for resilience to environmental stressors.

One of the most promising applications of genomic selection in aquaculture is in improving heat tolerance. A study on rainbow trout (*Oncorhynchus mykiss*) found that genomic selection can be used to identify markers linked to heat tolerance, enabling the development of strains better equipped to survive in warmer waters (Liu et al., 2020). By applying genomic selection to breeding programs, aquaculture species can be genetically tailored to thrive in environments that are expected to experience higher temperatures due to climate change.

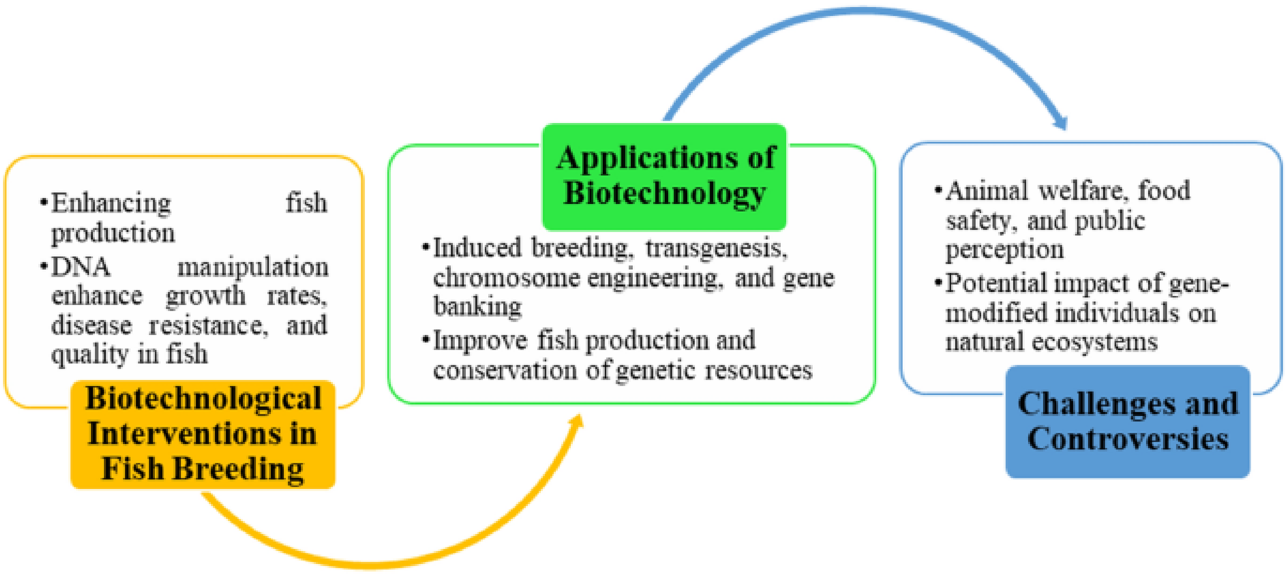

Figure 3.1. The role of biotechnology in enhancing fish production (Yang et al., 2021)

In addition to heat tolerance, genomic selection is being used to improve other climate-related traits, such as disease resistance and the ability to survive in low-oxygen environments. For example, genomic tools are being employed to identify genetic markers associated with resistance to the pathogen *Vibrio anguillarum*, which poses a significant threat to aquaculture species in warmer waters (Vázquez et al., 2018). By using genomic selection to breed fish that are more resistant to diseases, aquaculture systems can become more sustainable and less reliant on antibiotics, which are increasingly under scrutiny due to their environmental impact.

Genomic selection is also being integrated with traditional selective breeding to maximise genetic gain. The combination of genomic information with phenotypic data allows breeders to make more informed decisions about which individuals to select for reproduction. For example, genomic data can be used to predict the future performance of offspring, helping to avoid issues such as inbreeding and ensuring the long-term genetic health of aquaculture populations (Gjøen et al., 2018).

Integrating Selective Breeding and Genomic Selection. The integration of selective breeding and genomic selection is seen as a powerful strategy to ensure the resilience of aquaculture species in the face of climate change. Selective breeding provides a solid foundation by improving traits such as growth rate and disease resistance, while genomic selection accelerates the process and enhances the precision of breeding programs. Together, these techniques enable the rapid development of strains that are better suited to the changing environmental conditions.

In the case of Atlantic salmon, for example, both selective breeding and genomic selection have been employed to create strains that are more resistant to higher temperatures and diseases (Gjøen et al., 2018). The combination of these two approaches has the potential to significantly increase the sustainability of aquaculture by developing strains that can thrive in warmer, more variable environmental conditions.

Challenges and Future Directions. While biotechnological advances hold great promise for improving aquaculture breeding, some challenges need to be addressed. One of the key concerns is the potential for genetic homogenisation in farmed populations, which can lead to inbreeding depression and reduced genetic diversity. It is crucial for breeding programs to manage genetic diversity effectively, ensuring that aquaculture species remain adaptable to future environmental changes (Houston et al., 2018).

Moreover, the implementation of genomic selection requires significant investment in genomic resources, including the development of high-quality reference genomes and genetic markers. While genomic tools have become more accessible in recent years, the cost and complexity of these tools remain a barrier for some aquaculture industries (Huntingford et al., 2020).

Despite these challenges, the continued development of genomic technologies, combined with advances in computational tools and breeding strategies, holds great potential for improving the resilience of aquaculture species to climate change.

Biotechnological advances in aquaculture breeding, including selective breeding and genomic selection, offer promising solutions to the challenges posed by climate change. By enhancing the resilience of aquaculture species to rising temperatures, disease, and other environmental stressors, these technologies can help ensure the sustainability of the industry. The integration of genomic selection with traditional breeding approaches is likely to be a key strategy for developing more climate-resilient strains of fish and shellfish. As the aquaculture sector continues to face the pressures of climate change, these biotechnological innovations will play a critical role in ensuring that aquaculture remains a viable and sustainable source of food for the global population.

3. Genetic Engineering and CRISPR

1.1. Genetic Engineering in Aquaculture

The use of biotechnological methods to improve the well-being of cultured organisms, increase productivity, and protect aquatic ecosystems has yielded encouraging results. Vaccines and immunostimulants, probiotics, prebiotics, symbiotics, paraprobiotics, phage treatment, antimicrobial peptides, gene therapy, RNA interference, and other biotechnological therapies are among them. Genetic advancements in aquaculture play a crucial role in increasing productivity, reducing production costs, and minimising the environmental impact.

Examples of methods for editing fish genomes include CRISPR–Cas9, transcription activator-like effector nucleases, and zinc-finger nucleases. Molecular biology and transgenesis, gene banking, chromosome manipulation, hormonal treatments, raising fish with one or more parents, creating fish with different numbers of cells (polyploid, triploid, haploid, gynogenetic, and androgenetic), and the use of synthetic hormones in fish breeding are other methods used in fish biotechnology.

Innovations in biotechnological technologies have revolutionised fish genetic breeding, leading to significant advancements in the aquaculture industry (Yang et al., 2021).

Techniques such as genetic engineering and CRISPR–Cas9 have enabled the precise modification of fish genomes, resulting in strains with increased growth rates, disease resistance, and improved feed conversion efficiency. Selective breeding programs have been optimised through marker-assisted selection, allowing for the identification and propagation of desirable genetic traits more efficiently. Furthermore, reproductive technologies, including hormone-induced spawning and cryopreservation of gametes, have enhanced breeding success and genetic diversity. These biotechnological advancements have contributed to more sustainable and productive fish farming practices, meeting the increasing global demand for seafood. These tools play a crucial role in avoiding the extinction of endangered fish species and improving commercial fish production. Additionally, other biotechnological methods, such as the use of synthetic hormones, monosex production, and transgenesis, contribute to advancements in fish breeding. These tools play significant roles in preventing the extinction of endangered fish species and enhancing commercial fish production. Additionally, other biotechnological methods, such as the use of synthetic hormones, monosex production, and transgenesis, significantly contribute to advancements in fish breeding. Figure 3.2 shows the various biotechnological innovations in fish breeding (Sankaran & Mandal, 2024).

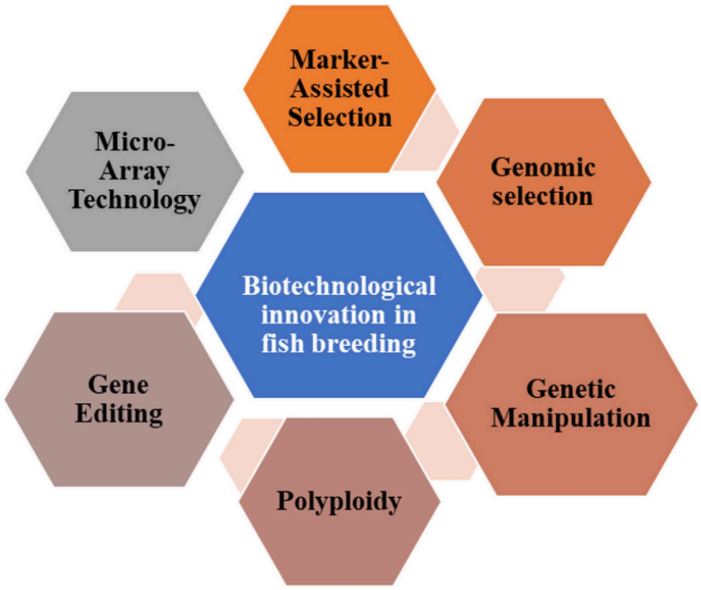

Figure 3.2. Biotechnological innovations in fish breeding

Genetic diversity represents a substantial resource that can be utilised to initiate selective breeding programs, which have been proven to improve the performance of the aquaculture sector significantly. Facilitating the transfer of training and technology across different aquaculture sectors can greatly benefit lower-value species, enhancing their productivity and sustainability.

An organism's genome can be modified by inserting synthetic DNA made from various sources using a process known as recombinant DNA technology. Implanting a genetic fragment containing our target gene into an existing genome is the first step in the procedure. In this technique, restriction enzymes, vectors, and host cells are utilised as tools. A variety of enzymes are involved in the processes of cutting, synthesising, and binding. Enzymes such as restriction enzymes are part of this group. To transport and incorporate target genes, vectors are a helpful tool. The applications of recombinant DNA technology include gene cloning, gene therapy, and agriculture. Figure 3.3 shows the various steps involved in recombinant DNA technology (Sankaran & Mandal, 2024).

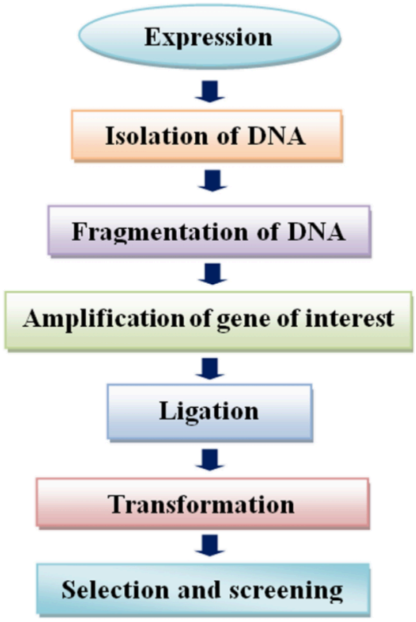

Figure 3.3. Main steps involved in recombinant DNA technology (Sankaran & Mandal, 2024)

1.2. CRISPR in Aquaculture

CRISPR–Cas9 represents a revolutionary tool in genetic engineering, enabling precise and targeted modifications of fish DNA to enhance traits such as pigmentation, growth, muscle quality, and disease resistance. This technology surpasses traditional breeding methods by offering a more cost-effective, straightforward, and precise approach to genetic enhancement. Its applications include improving growth performance (e.g., body weight, length, and muscle development), enhancing muscle quality, increasing disease resistance, and facilitating sex determination. Furthermore, CRISPR–Cas9 offers promising solutions for enhancing disease resistance by targeting immune-related genes and pathogen recognition pathways, thereby reducing the need for antibiotics and chemical treatments. This technology has significantly advanced aquaculture by genetically optimising key traits in fish species. For example, researchers have successfully manipulated germ cells in Atlantic salmon to control reproductive cell differentiation, improved feed conversion efficiency for growth in yellow catfish, achieved targeted gene modifications in tilapia, and minimised unintended off-target effects (Zhu et al., 2024).

Figure 3.4 shows the methods of CRISPR–Cas9 involved in gene editing. The Cas9 enzyme and guide RNA are the two main parts of the system. A streamlined variant of the CRISPR–Cas9 antiviral defence system found in bacteria serves as the basis for the CRISPR–Cas9 system. *In vivo* gene editing is made possible by inserting a synthetic guide RNA (gRNA) complexed with the Cas9 nuclease into a cell and then cutting the genome at a specific location. Because it enables easy, affordable, and precise *in vivo* genome editing, this method is profoundly important in biotechnology and medicine. In addition to its potential utility in pest and disease management, it has other potential applications in the development of novel agricultural products, genetically modified organisms, and pharmaceuticals. Additionally, it shows promise in the management of hereditary disorders and disorders caused by somatic mutations, including cancer. The CRISPR–Cas9 system provides a straightforward RNA-guided method for inducing targeted alterations at specific sites. Some phenotypes, such as eye colour or disease susceptibility, can be induced by these DNA alterations. The system employs RNA molecules designed to match target DNA sequences in conjunction with the Cas9 nuclease enzyme.

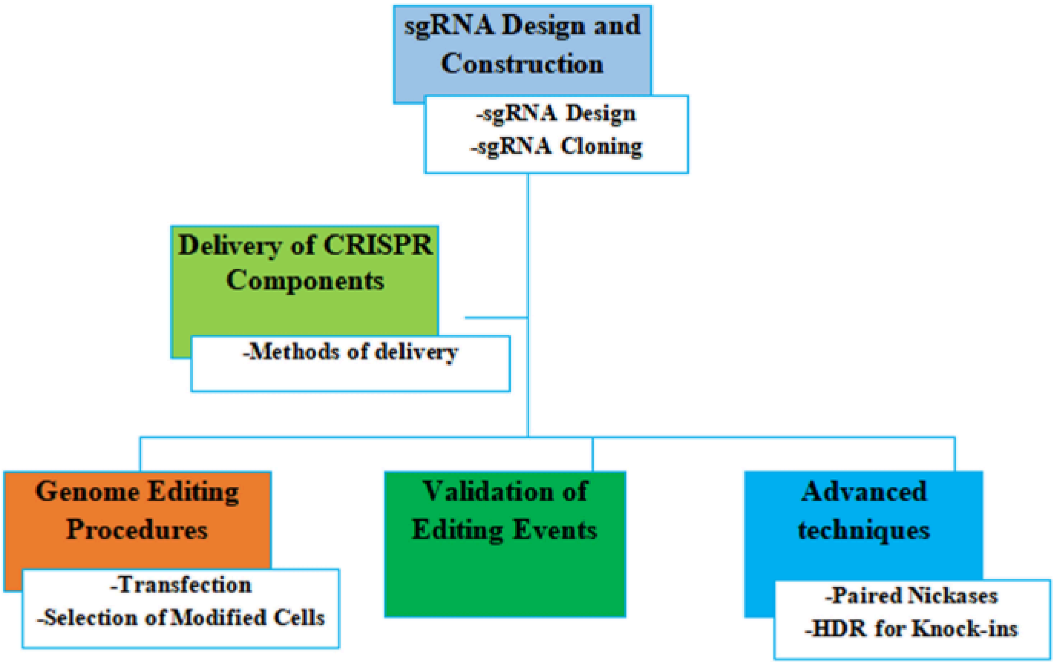

Figure 3.4. CRISPR–Cas9 gene editing (Sankaran & Mandal, 2024)

Although CRISPR–Cas9 has the potential to revolutionise the field of genetic engineering, it is not without its limitations. The accuracy of genome editing is a significant concern, as it results in permanent alterations to the genome. Additionally, its use in human germline genetic modification is highly controversial. In general, the utilisation of CRISPR–Cas9 gene editing can revolutionise the fields of biotechnology and medicine. However, exercising prudence and contemplating the ethical ramifications associated with its application are crucial (Sankaran & Mandal, 2024).

1.2.1. Disease Resistance

Disease resistance is a critical trait in aquaculture, reflecting a species' ability to withstand infections, poor water quality, and environmental changes. CRISPR–Cas9-mediated genome editing has emerged as a powerful method to enhance this resistance. By integrating antimicrobial peptide genes (AMGs) into fish genomes, CRISPR–Cas9 reduces bacterial colonisation, increases survival post-infection, and alters immune-related gene expression. This precision editing has led to significant advances, including enhanced resistance to infectious pancreatic necrosis (IPN) and bacterial cold-water disease in salmon, and the targeting of the JAM-A gene in grass carp to block viral entry, thereby conferring immunity to grass carp reovirus (GCRV).

In tilapia, CRISPR–Cas9 has edited genes linked to immune responses, improving resistance to bacterial pathogens like *Streptococcus agalactiae* and *Aeromonas hydrophila*. Similarly, in catfish, this technology has targeted immune-regulating genes, resulting in increased survival rates after pathogen exposure. These advances have been complemented by knock-in techniques that introduce foreign genes, improving disease resistance while enhancing growth and nutritional value in species such as tilapia and catfish (Zhu et al., 2024).

1.2.2. Fish growth and muscle quality

CRISPR–Cas9 has been instrumental in improving growth rates and muscle quality across aquaculture species, including Nile tilapia, channel catfish, common carp, and rainbow trout. By targeting growth hormone-related genes such as myostatin *(mstn)*, which inhibits muscle growth, researchers have achieved significant enhancements in body mass and muscle development. For instance, channel catfish with disrupted *mstn* genes showed a 29.7% increase in body weight. At the same time, similar modifications in olive flounder and red sea bream boosted muscle mass and optimised commercial fish size.

Beyond growth, CRISPR–Cas9 enables the study of developmental processes and the modeling of human diseases using zebrafish, a widely used organism for genetic research. Transgenic techniques have further advanced fish farming by overexpressing growth hormone genes in species such as Atlantic salmon, resulting in rapid growth and higher yields that help meet global protein demand. These genetic modifications, combined with optimised nutrition and selective breeding, enhance muscle texture and overall aquaculture efficiency (Zhu et al., 2024).

1.2.3. Off-Target Effects in CRISPR–Cas9

While CRISPR–Cas9 offers unparalleled precision, off-target effects remain a concern. These unintended edits can affect non-target genome regions, potentially causing adverse effects. Recent advancements, including high-fidelity Cas9 variants (e.g., SpCas9–HF1, eSpCas9), have significantly reduced off-target activity. Improved guide RNA (gRNA) design and algorithms, such as CRISPR–DO, have enhanced specificity. Additionally, novel tools like base and prime editors allow for precise genome modifications without inducing double-strand breaks, thereby minimising off-target mutations. Advanced delivery systems, such as nanoparticles and viral vectors, further increase accuracy in gene editing applications.

Zebrafish and other aquaculture species, including tilapia and Atlantic salmon, have benefited from these advancements. High-fidelity editing has enabled researchers to enhance growth, disease resistance, and other traits while maintaining genomic integrity.

The mechanism used by CRISPR–Cas9 in knockout genes in different fish species are indicated in Figure 3.5.

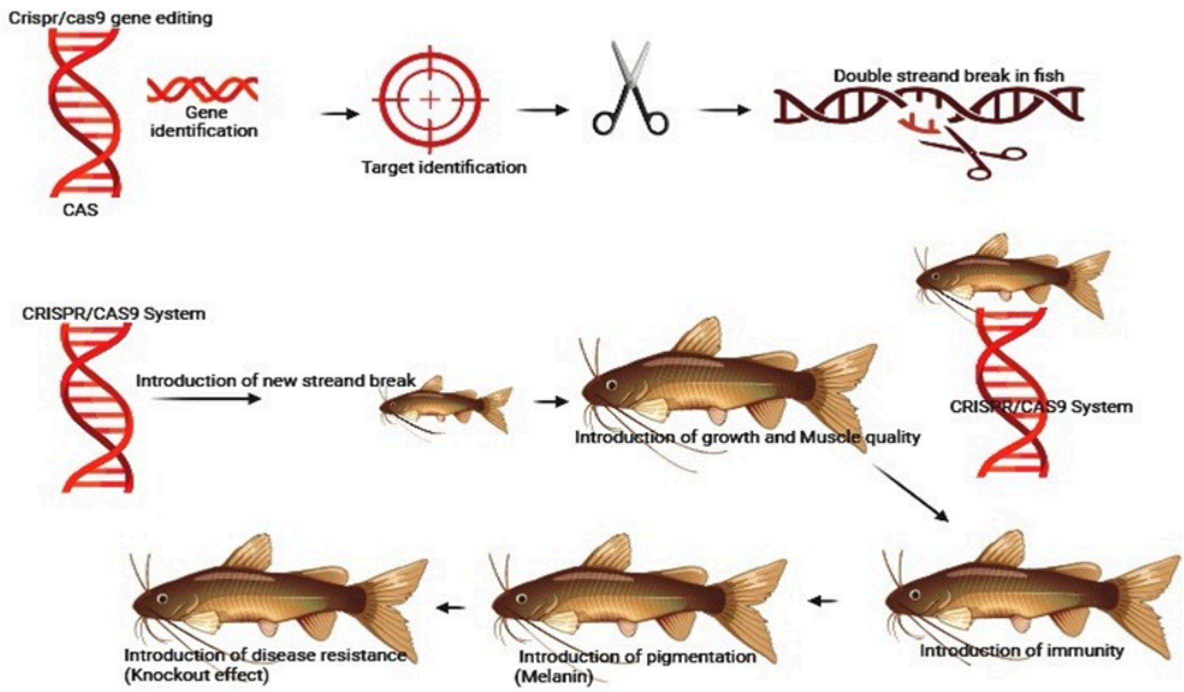

Figure 3.5. Steps of the application of CRISPR–Cas9 in aquaculture (First, a specific gRNA is designed to match the target gene sequence. Then, the Cas9 protein binds to the target DNA, causing a double-strand break. Finally, the break is repaired) (Zhu et al., 2024)

1.2.4. Sex Determination

Sex determination in fish involves genetic, environmental, and epigenetic factors, making it a complex but vital area of study in aquaculture. CRISPR–Cas9 has illuminated mechanisms of sex differentiation by precisely targeting relevant genes. For example, editing the *amh* gene in Nile tilapia resulted in phenotypic females from genetic males, demonstrating the gene's role in male sex determination. Similar studies in zebrafish have explored genes like *dmrt1* and *sox9a*, revealing the polygenic nature of sex determination in this species. Additionally, genome-wide CRISPR–Cas9 screenings have identified master regulators such as the *sdY* gene in rainbow trout, advancing our understanding of sex differentiation.

1.2.5. Effects of Using CRISPR–Cas9 in Gene Editing on Different Fish Species

CRISPR–Cas9 addresses challenges like disease outbreaks, poor growth rates, and environmental degradation in aquaculture. Its applications extend to controlling invasive species, engineering microorganisms for environmental remediation, and creating genetically modified fish for sustainable production. Genome editing offers solutions for enhancing fish traits while mitigating the ecological footprint of aquaculture. For example, transgenic fish with improved feed conversion efficiency reduce resource use, supporting environmentally friendly practices.

By enabling precise genetic modifications, CRISPR–Cas9 has transformed aquaculture, paving the way for sustainable and efficient fish farming practices. Continued advancements in editing techniques, ethical considerations, and environmental management will further optimise its application in the industry. Table 3.1 provides a summary of the traits most commonly targeted for genome editing in fish aquaculture (Blix et al., 2021).

Table 3.1. Effects of CRISPR–Cas9 on Biological and Environmental Aspects of Fish Species

Applicable Fields	Impacts
Disease resistance	It is used to reduce the viral hemorrhagic septicemia virus (VHSV) infection of olive flounder hirame natural embryo (HINAE) cells.
	It enables gene editing in fish species such as salmon, tilapia, and shrimp to increase their resistance to diseases.
	It helps in the deletion of the *JAM-A* gene in grass carp cells, which significantly enhances resistance to grass carp reovirus (GCRV) infection.
	It helps enhance fish cell lines for host response and genetic resistance against infectious diseases, using Atlantic salmon and rainbow trout as model systems in aquaculture.
Environmental adaptation	It helps to edit genes in fish species, such as farmed salmon, to adapt to changing environments.
Improved growth rates and muscles	It increases muscle growth by knocking out melanocortin (*mc4r*) receptor genes and has been experimentally tried on channel catfish and medaka fish.
	It improved the growth rates and increased muscle mass of the channel catfish by modifying the myostatin gene in channel catfish embryos.
	It helps increase the muscle mass of the blunt snout bream due to the disruption of the *mstn*.

CRISPR–Cas9 gene-editing technology has revolutionised aquaculture by enabling precise genetic modifications to improve traits such as disease resistance, growth, and sustainability. This tool also facilitates gene drives, increasing the inheritance rate of engineered genes to nearly 100%, accelerating the spread of desirable traits within populations.

Li et al. (2021) used CRISPR–Cas9 to create sterile, all-male Nile tilapia populations, resulting in faster growth rates and reduced ecological risks from escaped farmed fish. Similarly, Wargelius et al. enhanced disease resistance in Atlantic salmon by modifying genes essential for viral infection, addressing significant losses in aquaculture caused by pathogens like IPNV and SAV.

Other studies have leveraged CRISPR–Cas9 to enhance disease resistance in carp, tilapia, and catfish by targeting immune-related genes or pathogen recognition pathways. Growth-related gene editing has also yielded notable successes, such as *myostatin* knockouts in common carp, channel catfish, and red sea bream, leading to increased body size and growth rates.

CRISPR–Cas9's applications extend beyond production traits, enabling the creation of novel phenotypes. Examples include albino Nile tilapia and modified Pacific oysters with enhanced growth. The technology's versatility also spans species such as ridgetail shrimp, further demonstrating its transformative potential in aquaculture (Table 3.2).

Table 3.2. Applications of CRISPR–Cas9 in Various Fish Species and Their Impacts (Zhu et al., 2024)

Fish Species	Technological Impacts
Nile tilapia	It is used to produce sterile Nile tilapia populations, reducing the risk of environmental damage from escaped fish.
Atlantic salmon	It helps in gene editing to create species that are highly resistant to viral infections, e.g., salmon.
Zebrafish	It allows scientists to study mutations and genetic variants in zebrafish.
	It can be used to successfully integrate composite tags into zebrafish embryos, enabling precise labelling and visualisation of cellular structures or proteins. This offers potential for studying protein dynamics, gene expression, and other biological processes in this model organism.
Rainbow trout	It has been shown to reduce the expression of the igfbp-2b gene in rainbow trout, influencing growth and development. However, its impact on overall performance and the endocrine system remains unclear.
Atlantic salmon and Rainbow trout	It has been used to target unique genes associated with growth and immunity in Atlantic salmon, rainbow trout, and coho salmon cells.
Japanese medaka	It has the potential to increase muscle growth and body weight in farmed fish species such as medaka. However, further investigation is needed to determine its impact on production yield and fish health.
Olive flounder	It can be used to disrupt the myostatin gene in olive flounder, potentially increasing body weight and muscle tissue, but further research is needed to understand its effects on production efficiency and fish health.
Channel catfish	It has been used to modify the myostatin gene in Channel catfish to improve muscle growth and quality, but further research is needed to understand its effects fully.

4. Cryopreservation and Assisted Reproductive Technologies

1.3. Aquaculture and Cryopreservation

A variety of factors influence fish breeding, and even the most experienced hatchery operators often encounter partial or complete failures in the breeding process. To achieve the desired quantity of seeds, induced breeding is widely regarded as an effective method. This approach facilitates the maturation and spawning of fish under unfavourable conditions, such as inadequate rainfall or extreme climate scenarios. However, repeated breeding efforts can take a significant toll on the health of broodstock within their limited lifespan. Replacing broodstock is challenging due to logistical and physiological issues related to their transport. Consequently, the transportation of gametes has emerged as a promising alternative, offering benefits similar to those observed in animal husbandry.

The integration of biotechnological tools into fish breeding programs is essential for ensuring consistent and sustainable seed production. Cryopreservation presents a viable solution for producing high-quality seeds and genetically superior fish varieties. Recognising its potential, the Food and Agriculture Organization (FAO) has identified cryopreservation as a critical strategy for conserving fish genetic resources (Betsy et al., 2022).

Cryopreservation refers to the preservation of biological samples at extremely low temperatures, effectively arresting metabolic activities and preserving the structural and functional integrity of these samples for indefinite periods. This technology has become a cornerstone of reproductive biology, offering critical benefits for livestock and aquaculture industries. By maintaining temperatures below –130°C, metabolic activities cease entirely, enabling biological samples, such as cells, tissues, and even whole organisms, to remain viable upon thawing. Cryopreservation holds particular importance for preserving valuable genetic material, enhancing breeding programs, and supporting biodiversity conservation efforts (Fletcher & Rise, 2012).

Mechanisms of Preservation

Cryopreservation enables the preservation of gametes for extended periods, often spanning several years, without significantly affecting their fertilisation capacity. By lowering the temperature to approximately −196°C, all biological and biochemical activities are halted, preventing processes that lead to cell death and DNA degradation. This technique is a powerful tool for supporting the long-term sustainability of aquaculture and biodiversity conservation.

However, ice formation within biological systems presents a significant challenge, as it can lead to mechanical damage and osmotic imbalance. Controlled cooling processes ensure that ice forms extracellularly, thereby creating a concentration gradient that facilitates water efflux from cells. This process prevents lethal intracellular ice formation. Advances in cryoprotective agents (CPAs) have been pivotal in mitigating these damages, allowing for the successful preservation of diverse cell types, tissues, and small biological structures. By refining the interplay between cooling rates, CPA concentrations, and cell-specific characteristics, researchers have enhanced cryopreservation outcomes.

Cryoprotective Agents

Cryoprotective agents play a crucial role in reducing intracellular ice formation and preserving protein and membrane integrity during freezing and thawing. These agents fall into two categories: permeable and non-permeable. Permeable CPAs, such as DMSO, glycerol, and methanol, penetrate the cell membrane to balance intracellular and extracellular osmotic pressures. Non-permeable CPAs, including sugars and specific proteins, primarily act extracellularly to modify the solution's freezing point and provide additional protection. Despite their benefits, CPAs must be used cautiously, as they can induce toxicity, osmotic stress, and chromosomal abnormalities if misapplied. Balancing protective effects and potential adverse outcomes is a critical area of ongoing research.

Cooling and Thawing Protocols

The success of cryopreservation largely depends on the precise control of cooling and thawing protocols. Controlled freezing rates, typically ranging from −40°C/min to slower rates, are essential for minimising ice crystal formation. Specialised biofreezers and nitrogen vapor methods are widely used to achieve these controlled conditions. Conversely, thawing must be rapid to prevent ice recrystallisation, which can severely damage cellular structures. Emerging technologies, including programmable freezing devices and advanced thawing techniques, aim to standardise and optimise these processes for various biological materials, thereby improving survival rates and functional recovery (Fletcher & Rise, 2012).

1.3.1. Gamete Cryopreservation

Sperm Cryopreservation

Sperm cryopreservation represents one of the most successful applications of cryobiology, with well-established protocols in livestock and expanding applications in aquaculture. However, fish sperm exhibit significant differences from those of mammals, necessitating unique approaches. Key characteristics of fish sperm include their immotility in seminal plasma, activation of motility upon exposure to activating solutions, high sensitivity to osmotic changes, and relatively low ATP production. These unique traits underscore the need for tailored cryopreservation strategies to ensure viability and functionality upon thawing.

Developing effective protocols for fish sperm cryopreservation involves several critical steps:

- **Sperm Collection**. Obtaining high-quality sperm free from contaminants is essential. Techniques such as abdominal massage, aspiration, or direct extraction from the testes are commonly employed, depending on the species. Care must be taken to avoid contamination with substances like urine, which can prematurely activate motility.
- **Quality Analysis**. Evaluating sperm quality is crucial for selecting samples suitable for freezing. Parameters such as motility, viability, pH, and osmolality are assessed, often using advanced computerised systems to ensure accuracy.
- **Extender Formulation**. Extenders are buffered solutions designed to prevent premature activation of motility and to provide an optimal environment for freezing. Standard components include glucose, egg yolk, antioxidants, and CPAs like DMSO or glycerol. The choice of extender varies by species and specific requirements.
- **Freezing and Thawing**. Sperm is typically loaded into French straws or cryovials and frozen at controlled rates before being stored in liquid nitrogen (−196°C). Thawing must be conducted rapidly in a water bath to ensure maximum viability. Figure 3.6 illustrates the sperm freezing procedures

Figure 3.6. Sperm freezing process: (A) trout sperm extraction by canulation, (B) dilution in a cryoprotectant extender, (C) loading in 0.5 cc French straws (insert with different straws, cryovials, and PVA powder for straw sealing), (D) freezing over a floating device in a styrofoam box containing N2l, (E) storage in a N2l tank, (F) female stripping, (G) sperm thawing in a water bath, and (H–J) fertilisation (Fletcher & Rise, 2012)

Oocyte Cryopreservation

Unlike sperm, oocytes present significant challenges for cryopreservation. Their large size, complex structure, and limited permeability to CPAs make them highly susceptible to cryodamage. Issues such as chilling sensitivity, intracellular ice formation, and CPA toxicity are particularly pronounced. Moreover, the presence of multiple membrane layers and high lipid content further complicates the preservation process.

Recent research has focused on preserving oocytes at early developmental stages, where their structural simplicity may reduce susceptibility to cryodamage. Strategies include stepwise CPA removal to minimise toxicity, studies on chilling resistance, and the application of vitrification techniques. Vitrification, which involves ultrafast freezing with high CPA concentrations, offers a promising alternative by eliminating ice crystal formation. However, challenges remain in achieving uniform CPA distribution and minimising toxicity.

1.4. Embryo cryopreservation

The cryopreservation of fish embryos, which aims to preserve both maternal and paternal genetic material, has significant potential for enhancing aquaculture reproductive management. Despite its promise, the successful cryopreservation of fish embryos remains a challenge due to the biological complexities of these embryos, including their large size, multicompartmental structure, and limited permeability to cryoprotective agents (CPAs). These factors, combined with the presence of barriers like the yolk syncytial layer (YSL), hinder the effective distribution of CPAs and water throughout the embryo (Fig. 3.7, Hagedorn et al., 1997).

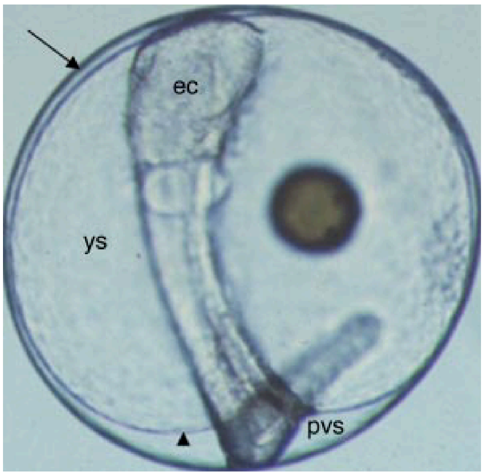

Figure 3.7. Turbot embryo at the tail bud stage showing the different envelopes and compartments: chorion (arrow), yolk syncytial layer (arrowhead), yolk sac (ys), perivitelline space (pvs), and embryo compartment (ec) (Hagedorn et al., 1997)

One major obstacle is the high-water content in embryos, which can lead to ice formation and cellular damage during freezing and thawing. Early-stage embryos, which theoretically offer simpler structural properties for preservation, are susceptible to chilling and CPA toxicity, further complicating cryopreservation efforts.

Studies on chilling sensitivity in fish embryos have shown that early developmental stages are more vulnerable to low temperatures than later stages. Strategies to mitigate chilling injuries include modifying the embryo's structure and using protective substances, such as antifreeze proteins (AFPs). These approaches have shown potential to enhance resistance to low temperatures but have not yet achieved consistent success.

The use of vitrification, a technique that eliminates ice formation through ultrafast freezing, has been proposed as a way to overcome these challenges. However, vitrification requires high concentrations of CPAs, which can be toxic and difficult to distribute evenly within the embryo due to its limited permeability. Various experimental techniques, such as increasing embryo permeability and improving CPA delivery systems, are being explored to address these limitations.

Recent advancements include methods to bypass barriers, such as the YSL, and improve CPA penetration. Techniques such as microinjection of CPAs or genetic engineering to enhance embryo permeability have shown promise. Additionally, the use of natural antifreeze proteins has demonstrated potential in reducing ice crystal formation and mitigating freezing-induced damage.

Although these methods are still in experimental stages, they offer valuable insights into the future of embryo cryopreservation.

Overcoming the challenges of fish embryo cryopreservation will require interdisciplinary collaboration and technological innovation. Efforts are focused on enhancing cryoprotection at the cellular level and improving techniques for CPA delivery. Promising directions include the use of advanced laser technologies to create temporary pores in embryos and the development of genetically modified strains with enhanced resistance to freezing damage.

Through continued research, fish embryo cryopreservation has the potential to become a reliable tool for aquaculture, supporting the preservation of genetic resources and promoting sustainable practices in fish farming.

Cryopreservation technology has been developed for many fish species (Betsy et al., 2022):

- This technology can be used to preserve the milt of the best age group brooder, which can be used at any point in time in the future.
- It can also eliminate the inbreeding problem since cryopreserved spermatozoa can be easily exchanged between hatcheries.
- Using this technology, spermatozoa can be made available at any season of the year.
- It makes breeding possible during the off-season.
- It synchronises the gamete availability of both sexes, leading to sperm economy.
- It simplifies broodstock management in farms.
- It helps in the production of viable and strong offspring by intra-species hybridisation.
- It overcomes the difficulties arising due to the short time viability of gametes.
- It enables the genetic preservation of desired lines.
- It allows cross-breeding at different times of the year.
- It helps in germplasm storage for genetic selection programs or conservation of species.
- Cryopreserved spermatozoa can help in the hybridisation programs and genetic engineering research in fish.
- It leads to many other avenues, such as cryobanking of viable gametes, as in the case of animal production and development of gene banks and genetic manipulation in fish.

Cryopreservation represents a transformative tool in aquaculture biotechnology, offering significant benefits for genetic preservation, breeding programs, and biodiversity conservation. While challenges remain, particularly in embryo and oocyte preservation, ongoing advancements in cryoprotective methods, genetic tools, and interdisciplinary research hold promise for overcoming these barriers. Future developments will likely expand the scope and efficiency of cryopreservation, ensuring its broader application in aquaculture and beyond. Through continued innovation, cryopreservation is poised to play a crucial role in supporting the sustainable growth of aquaculture and preserving aquatic biodiversity (Fletcher & Rise, 2012).

5. Ethical, Environmental, and Regulatory Considerations

1.5. Ethical Concerns in Aquaculture Biotechnology

Animal Welfare in Genetic Modification

The ethical implications of genetic modification in aquaculture are profound, particularly regarding animal welfare. Genetic interventions, such as transgenesis and gene editing, often aim to enhance production traits, including growth rates, disease resistance, and environmental tolerance. However, these modifications can inadvertently cause physiological stress or health complications. For instance, accelerated growth in transgenic fish may lead to skeletal deformities, reduced immune function, or altered metabolic rates. Critics argue that prioritising productivity over welfare may compromise the ethical treatment of these organisms, raising questions about the balance between innovation and humane practices.

The confined nature of aquaculture systems further amplifies these concerns. Fish reared in such environments are often subjected to high stocking densities, which leads to stress, susceptibility to disease, and behavioural changes. Ethical considerations extend to whether genetically modified fish are more or less suited to thrive in such conditions compared to their wild counterparts. Developing welfare metrics specifically tailored for genetically altered aquatic species is essential to ensure their quality of life is not unduly compromised.

Ecological Integrity and Biodiversity

Beyond individual welfare, ethical concerns encompass the broader ecological impacts of biotechnological interventions. The introduction of genetically modified or selectively bred species into aquaculture systems or natural habitats poses risks to ecological integrity. For example, transgenic fish with enhanced growth rates may outcompete native species for resources, disrupting local ecosystems and potentially leading to the decline or extinction of wild populations. These concerns underscore the moral responsibility of ensuring that biotechnology applications do not undermine the biodiversity and resilience of aquatic ecosystems.

The ethical debate also touches on human stewardship of biodiversity. While biotechnology can aid in conservation efforts, such as through cryopreservation of endangered species' genetic material, it also raises questions about humanity's right to alter genetic codes for economic or ecological purposes. Striking a balance between leveraging biotechnology for positive outcomes and preserving the natural evolutionary processes of aquatic species remains a key ethical challenge.

1.6. Regulatory Frameworks

Global Standards and Guidelines

The governance of biotechnological applications in aquaculture is a complex and evolving field. International organisations such as the Food and Agriculture Organization (FAO) and the Convention on Biological Diversity (CBD) have established frameworks to guide the safe and ethical use of biotechnology. These guidelines emphasise the precautionary principle, advocating for thorough risk assessments and monitoring before the approval and release of genetically modified organisms (GMOs) into aquaculture systems.

One key aspect of global standards is harmonising regulations across countries to ensure consistency in safety measures and environmental protections. This is particularly important given the transboundary nature of aquatic ecosystems and the potential for escapees to impact the waters of neighbouring nations. Collaboration among countries through treaties and agreements plays a crucial role in establishing uniform practices and mitigating risks.

National Regulatory Approaches

At the national level, regulatory frameworks vary widely, reflecting differing priorities, technological capacities, and societal attitudes toward biotechnology. Some countries, such as the United States and Canada, have robust systems in place for evaluating the safety and efficacy of genetically modified organisms, including extensive review processes that involve scientific, environmental, and public health assessments. In contrast, other regions may lack comprehensive regulatory structures, leading to gaps in oversight and potential risks.

Regulatory approaches often involve multi-step processes, starting with laboratory testing and progressing through controlled field trials before full-scale implementation. These processes aim to evaluate the environmental, economic, and social implications of new biotechnologies. Public consultation and transparency are increasingly recognised as critical components of regulatory frameworks, fostering trust and ensuring that decisions reflect societal values.

Safety Assessments and Approval Processes

Safety assessments are central to regulatory frameworks, providing a scientific basis for evaluating the potential risks of biotechnology applications. These assessments typically address several key areas:

- **Environmental Risks**. Evaluating the likelihood of escape and the potential ecological impacts of GMOs, including competition with native species, hybridisation, and habitat modification.
- **Human Health Risks**. Ensuring that genetically modified fish intended for consumption are free from allergens, toxins, or unintended genetic effects that could harm consumers.
- **Ecosystem Monitoring**. Implementing post-approval monitoring programs to detect and mitigate unforeseen impacts, ensuring long-term sustainability.

Approval processes often involve coordination among multiple agencies, including environmental, agricultural, and public health authorities. Rigorous scientific evaluations, combined with public input, aim to balance innovation with safety and ethical considerations.

1.7. Environmental Impacts of Aquaculture Biotechnology

1.7.1. Risk management

One of the most significant environmental risks of aquaculture biotechnology is genetic pollution, where genes from genetically modified or selectively bred species are transferred to wild

populations. This can occur through interbreeding, leading to genetic homogenisation and the loss of locally adapted traits in wild species. The long-term consequences of such genetic introgression include reduced resilience to environmental changes and a decline in biodiversity.
The effects of domestication selection on the genetic and phenotypic characteristics of aquaculture animals can lead to various potential environmental impacts upon their release into the wild. Fig. 3.8 summarises the mechanisms responsible for such impacts within four categories: direct ecological effects, indirect ecological effects, direct genetic effects, and indirect genetic effects.

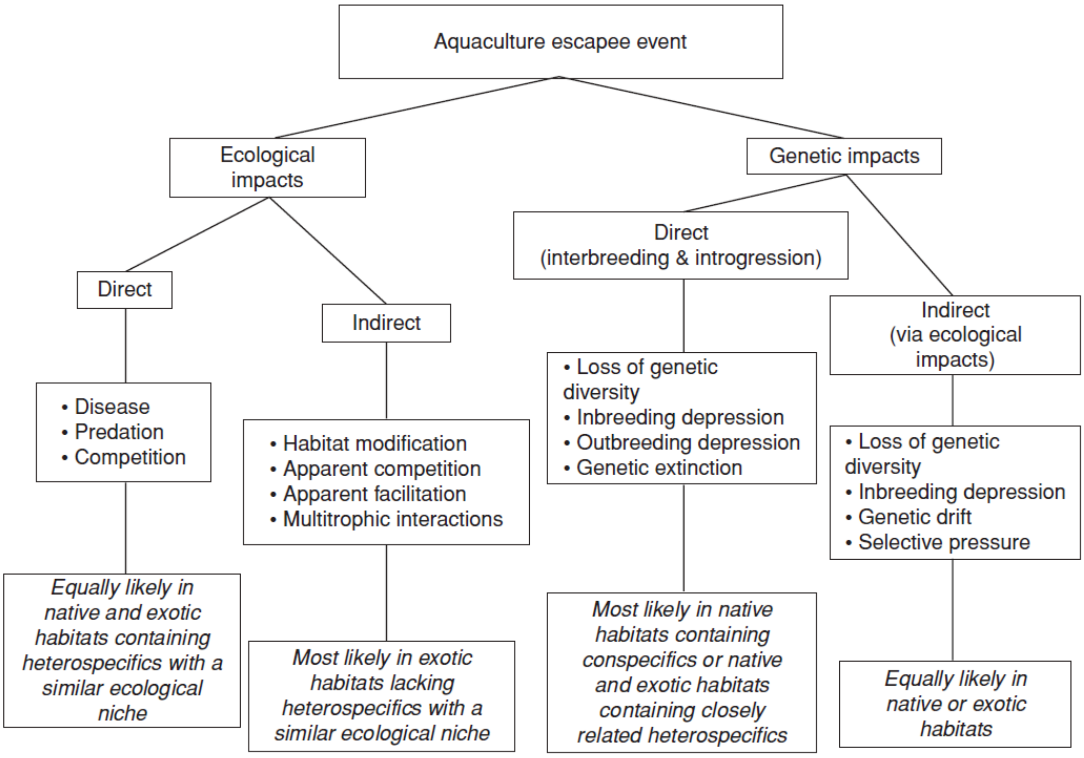

Figure 3.8. Possible environmental impact of aquaculture escapees

Aquaculture systems are particularly vulnerable to escape events, where farmed fish enter natural ecosystems. These escapees can outcompete wild populations for resources, introduce diseases, and disrupt the dynamics of food webs. Mitigating these risks requires robust containment strategies, such as physical barriers, and the development of sterile, genetically modified fish to prevent reproduction in the wild.

Interactions with Wild Populations

Interactions between farmed and wild populations extend beyond genetic impacts. Transgenic fish with enhanced traits, such as faster growth or greater disease resistance, may have ecological advantages over their wild counterparts. These advantages can lead to shifts in predator-prey relationships, altered competition dynamics, and changes in habitat use.

Research into the behaviour and ecological roles of genetically modified fish is essential to anticipate and manage these interactions. Long-term ecological studies, combined with predictive modelling, can help identify potential risks and guide management practices.

Long-Term Sustainability

Ensuring the long-term sustainability of aquaculture biotechnology requires a holistic approach that considers ecological, economic, and social dimensions. This includes minimising habitat destruction, optimising resource use, and protecting wild populations. Advances in biotechnology, such as the development of environmentally friendly feeds and improvements in waste management systems, can contribute to more sustainable aquaculture practices.

Monitoring and adaptive management are critical components of sustainable aquaculture. By continuously assessing the environmental impacts of biotechnological interventions and adjusting practices accordingly, stakeholders can balance productivity with ecological responsibility

1.7.2. Balancing Progress and Responsibility

The integration of biotechnology into aquaculture presents immense opportunities for addressing global challenges, including food security and biodiversity conservation. However, this progress must be accompanied by a strong commitment to ethical principles, rigorous regulatory oversight, and proactive environmental stewardship. By fostering collaboration among scientists, policymakers, industry stakeholders, and the public, aquaculture can evolve in a manner that is both innovative and sustainable.

Ethical, environmental, and regulatory considerations are not merely obstacles to overcome but are integral to the responsible advancement of aquaculture biotechnology. Through careful planning, transparent decision-making, and ongoing research, the sector can realize its potential while safeguarding the well-being of aquatic ecosystems and the communities that depend on them (Fletcher & Rise, 2012).

Summary

Global warming has significantly disrupted the breeding cycles, growth rates, and survival of aquatic species. Rising water temperatures alter spawning times and metabolic rates, leading to mismatches with food availability and suboptimal conditions for larval development. Species like Atlantic cod and European perch are breeding earlier, resulting in reduced survival rates for their offspring. Additionally, elevated temperatures can decrease oxygen levels in water, stressing larvae and affecting juvenile development. While some species demonstrate genetic adaptations to cope with these changes, rapid environmental shifts often outpace the ability of populations to adapt, leading to long-term declines.

Aquaculture has leveraged biotechnology to mitigate these challenges and enhance the resilience of farmed species. Selective breeding programs focus on traits like heat tolerance, disease resistance, and growth efficiency. Genomic selection accelerates this process by using genetic markers to propagate desirable traits. For instance, Atlantic salmon have been bred to tolerate higher temperatures and hypoxic conditions. At the same time, genomic tools have been employed to develop disease-resistant strains of rainbow trout and other species.

CRISPR–Cas9 technology has emerged as a revolutionary tool in aquaculture, enabling precise and targeted modifications to fish genomes. This method enables the enhancement of key traits, including growth, muscle quality, disease resistance, and environmental adaptation. For instance, genetic modifications in species like Nile tilapia and channel catfish have resulted in faster growth rates and improved muscle development by targeting the myostatin (*mstn*) gene. Similarly, CRISPR–Cas9 has been employed to enhance disease resistance in Atlantic salmon and grass carp by editing immune-related genes and pathogen recognition pathways.

In addition to improving individual traits, CRISPR has applications in sex determination and population management. Techniques such as creating sterile populations reduce ecological risks associated with escaped farmed fish. Despite these advancements, the technology is not without challenges. Off-target effects and ethical concerns surrounding genome editing, particularly in terms of animal welfare and ecological risks, necessitate robust regulatory oversight and further research.

Cryopreservation is another pivotal technology, offering solutions for the conservation of genetic resources and enhancing breeding efficiency. By preserving gametes and embryos at ultra-low temperatures, this technique supports biodiversity conservation and breeding programs across seasons and geographical regions. However, challenges such as chilling sensitivity and cryoprotectant toxicity, especially in oocytes and embryos, highlight the need for ongoing research to optimise protocols and improve success rates.

The integration of biotechnology into aquaculture raises profound ethical and environmental questions. The potential for genetically modified organisms (GMOs) to escape into natural ecosystems and interbreed with wild populations poses risks to genetic integrity and biodiversity. Regulatory frameworks at both national and international levels play a crucial role in addressing these concerns, emphasising risk assessments, monitoring, and public engagement. Ethical considerations extend to animal welfare, particularly in ensuring that biotechnological interventions do not compromise the health and well-being of farmed species.

The future of aquaculture depends on striking a balance between technological progress and sustainability. Innovations such as CRISPR–Cas9 and genomic selection hold immense potential to enhance resilience and productivity. However, interdisciplinary collaboration, robust governance, and environmental stewardship are crucial to minimising ecological impacts and ensuring long-term viability. By prioritising ethical practices and sustainability, aquaculture can play a pivotal role in addressing global food security challenges and conserving aquatic biodiversity.

This chapter emphasises the importance of addressing the interconnected challenges of climate change and aquaculture sustainability through innovative and responsible biotechnological solutions. By leveraging the potential of these advancements, the aquaculture industry can contribute to global efforts in biodiversity conservation, climate resilience, and food security.

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Chapter 4. Changes in Feed and Feeding Practices in Aquaculture Due to Global Warming

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Introduction

Aquaculture is one of the fastest-growing agricultural sectors globally and is increasingly important for producing sustainable and healthy diets with relatively low climate impacts. Fish farming is predicted to grow by 32% by 2030 (FAO, 2020). Market forces agree that encouraging the growth of European aquaculture is the most viable way to meet the increasing demand for fish supplies. However, it is challenging to achieve sustainable production that contributes to healthy diets, meets the Sustainable Development Goals, and aims for Net Zero (Messeder, 2021). Under climate change, it is estimated that nutrient availability will decrease (Cheung et al., 2023). The scarcity of high-quality feed and feed ingredients, as well as concerns about the safety and quality of aquatic products, pose significant challenges to the sustainable development of this sector (Ma & Hu, 2023).

Fish farming generates approximately 250 million tons of CO_2 equivalents annually worldwide (MacLeod et al., 2020). Salmon farming generates approximately 10 million tons of CO_2 equivalents annually. Feed accounts for an average of 75% of the greenhouse gas emissions (GHGs) associated with salmon production in Norway (Ziv-Douki, 2020). Compared to livestock production, especially beef, seafood production has lower carbon emissions.

Changes in temperature lead to poor growth and survival of cold-water species, deterioration of water quality, a weakened immune system in cold-water species, a weakened ocean carbon sink capacity, and an increased virulence of pathogens in warmer water. Since feed contributes significantly to the carbon footprint of aquaculture farming, significant emissions reductions in feed production should be targeted (Zhang et al., 2024).

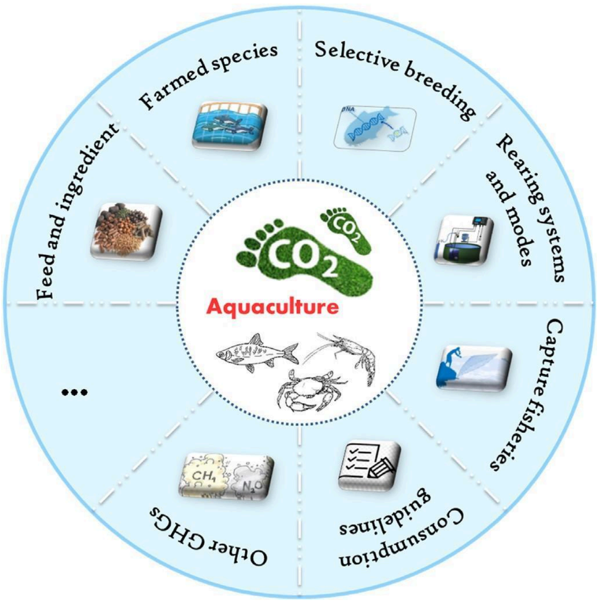

Figure 4.1. Intervention sectors for reducing carbon emissions in aqua- culture (adapted from Zhang et al., 2024).

1. Changes in Nutritional Physiology

1.1. Temperature and Metabolism

Aquaculture is inherently more sensitive to the impacts of climate change because of its heavy reliance on the environment. Global warming increases water temperatures, which can elevate the metabolic rates of aquaculture species, necessitating changes in feed formulation to meet heightened nutritional demands (Reid et al., 2019). The basal energy requirements of fish, which are poikilothermic animals, are directly affected by water temperature. As temperature increases, their standard metabolic rate increases, and so do their maintenance energy and protein requirements. Furthermore, the degree to which temperatures within the optimum range affect basal metabolism varies by species. Climate change is one of the most significant stress factors in aquaculture.

1.2. Digestion and Nutrient Absorption

Temperature-induced changes in metabolic rate affect not only the energy of the diet but also the feed efficiency ratio (FER, gain/feed) or feed conversion ratio (FCR, feed/gain). A water temperature difference of a few degrees can produce significant differences in feed conversion in some species (Siikavuopio et al., 2012). FCR changes caused by variations in water temperature may also lead to alterations in the digestibility of specific nutrient categories, such as fatty acids in salmonids (Huguet et al., 2015). On the other hand, it can be said that the effect of water temperature on nutrient digestibility in aquatic animals is generally minimal. In this regard, studies conducted with salmon have shown that protein and lipid digestibility may show small changes with temperature (Amin et al., 2014). Some studies show that the ‘intestinal transit time of feeds’ may be affected by warmer water, depending on the species. Studies emphasise that high water temperatures will have a minimal effect on the nutrient or energy digestibility of aquatic animals until the optimum range is exceeded (Reid et al., 2019).

Feed Intake and Metabolic Rate

Global warming and the resulting climate changes lead to the warming and acidification of water bodies, as well as changes in precipitation and wind patterns, which in turn affect water currents, turbulence, and turbidity. These changes affect the nutrition and endocrine systems of aquatic animals (Nadermann et al., 2019). Climate change and changes in the aquatic environment, caused by the release of carbon dioxide (CO_2) and methane into the atmosphere, can also impact fish physiology and behaviour, as well as the feeding and endocrine control of feeding (Ahmed et al., 2019; Volkoff, 2019).

Fish, being ectothermic creatures, are susceptible to changes in water temperature. Increases in water temperature lead to higher oxygen consumption and metabolic rates, resulting in increased energy requirements (Sandblom et al., 2014). Although these changes vary by species, feed intake in fish increases with moderate temperature increases (Sharma et al., 2017). Studies show that increases in CO_2 and low water pH reduce food intake in fish, disrupting their ability to perceive chemical signals and detect food by affecting their sense of smell (Porteus et al., 2018). Since fish require increased muscle movements to maintain balance in turbulent waters, they also increase their energy expenditure. Additionally, low visibility conditions negatively affect fish feeding.

Effect of Climate Change on Microflora or Microbiota in Fish

The morphology of the fish digestive system has a direct effect on the digestive capacity and immune status of fish. However, they are also vulnerable to heat stress, which affects their health (Geda et al., 2012). It is known that heat stress can have adverse effects on the villi and absorption area in the digestive system of various animal species, such as pigs and chickens. However, the effects of heat stress on the morphology of fish intestines are not fully understood. Gut microbiota generally interacts with the host intestine in a complex manner and participates in nearly all physiological processes, including metabolism and immunity (Gardiner et al., 2020; Yadav & Jha, 2019), and is sensitive to temperature changes. Increased water temperature has been shown to cause a decrease in beneficial lactic acid bacteria and an increase in potentially dangerous *Vibrio* spp. in Atlantic salmon (*Salmo salar*) (Amin et al., 2016). However, the effects of heat stress on gut microbiota appear to be species-specific.

The microbiome is widely recognised as an important component in maintaining the overall health of fish, as supported by numerous studies (Legrand et al., 2020). Temperature is a crucial nonbiological factor influencing the physiological state of animals; this is particularly true for aquatic organisms, where body temperature fluctuates in response to water temperature (Sepulveda & Moeller, 2020). Stress can disrupt the intestinal microbial structure, thereby affecting the physiological and immune systems of fish (Blacher et al., 2017). In addition to altering the structure of the intestinal microbiota, temperature can also affect host metabolism and lead to changes in phenotype (Guillen et al., 2019). Trinh et al. (2017) found significant differences in the intestinal microbiota of juvenile fish with different growth rates. They suggested that the microbiota may affect the growth rate of juvenile fish by enhancing energy metabolism gains. Rimoldi et al. (2020) showed that the dominant intestinal microbiota can be used to assess the health status of European sea bass.

2. Sustainable Feed Ingredients in Aquaculture

Aquaculture could produce animal protein with lower GHGs emissions than land-based animal agriculture (Hilborn et al., 2018). Therefore, aquaculture is a more climate-friendly protein production sector than other livestock sectors (NOAA Fisheries, 2022). Aquaculture feeds use more than 70% of the World's fish meal and fish oil (FMFO). Globally, approximately 30 million tons of small fish are captured in the ocean each year, with around 17 million tons used in aquaculture feeds (Cottrell et al., 2020). Thus, the use of alternative protein sources for aquaculture feed can reduce the environmental impact of aquaculture, potentially produce a more cost-effective feed, and develop a competitive sector. Alternative protein sources, such as insect meal, are not new, but recent investments in this sector are bringing them closer to being ready for the market. A good example of this is the new initiatives launched to help salmon farmers reduce their environmental footprint by 30% by 2030. Other feed sources, particularly seaweed/algae, should be further developed. The exploration of industrial biotechnology-based feeds is another emerging area. Extrusion increases the digestibility and absorption of nutrients in feed (Zhang et al., 2024).

2.1. Alternative Feed/Protein Sources

In the EU, protein production is expected to double by 2050. However, since the EU is not self-sufficient in protein production, around 70% of feed proteins are imported. Therefore, the EU needs to find sustainable alternative protein sources that can be produced economically in quantities sufficient to meet the growing demand of the food and feed industry (Smárason, 2023). The sustainability of feed resources for aquaculture is primarily dependent on the availability of high-quality feed ingredients, such as FMFO. These traditional feed ingredients are under increasing pressure due to the rapid expansion of aquaculture for human consumption, the decline in fish captured, and climate change (Idenyi et al., 2022).

More than 90% of GHGs in aquaculture are generated by the fish feed used. The circular economy approach can be applied in fish farm feed production using new biomaterials to help achieve climate change targets (Tait, 2021). Today, approximately 70% of the total global aquaculture production by weight depends on the supply of external feed inputs. This situation presents one of the biggest challenges to the future sustainability of aquaculture, necessitating the development of alternative feed ingredients (Reid et al., 2019).

Limited and decreasing global capture fishing is leading to a decline in global fishmeal production (approximately 5 million tons per year) and fish oil production (approximately 1 million tons per year). Because 60-80% of this fish meal and approximately 70–80% of fish oil are used in aquaculture (FAO, 2022). Considering the increasing demand for FMFO resulting from the ever-growing aquaculture industry, it is essential to find suitable substitutes for FMFO to support sustainable aquaculture.

Fish Meal and Fish Oil (FMFO) as Main Feed Ingredients for Aquaculture

Aquaculture is a production line using 'fed' species such as shrimp, sea bass, and salmon, and 'unfed' species such as silver carp, seaweed, and oysters. Traditionally, fed aquaculture has relied on aquafeeds containing high levels of FMFO (Froehlich et al., 2018). However, FMFO use is considered a leading unsustainable factor in aquaculture because it increases the pressure on fish stocks and disrupts the balance of aquatic food webs (Hua et al., 2019). The dependence on fish-based feeds for aquaculture poses a threat to marine biodiversity and food security. As is known, climate change and El Niño harm many natural aquatic food sources, particularly phytoplankton. For these reasons, the amount of FMFO used in aquatic feeds has been decreasing over the years. Another problem caused by fishmeal is the increased accumulation of heavy metals, chemicals, and microplastics in marine fish (Hanachi et al., 2019).

Plant-based Feeds/Oils and Environmental Challenges

In recent years, aquaculture feed producers have been turning to agricultural products, such as soy, corn, and canola, instead of FMFO. The use of transgenic seeds, water, pesticides, and fertilizers in the production of these products has a negative impact on environmental sustainability. Therefore, replacing FMFO ingredients with terrestrial product ingredients seems to be far from meeting the goal of having a zero-carbon footprint. They also have low nutrient quality, poor digestibility, and deficiencies in essential amino acids such as lysine, threonine, and tryptophan. For this reason, it is still not possible to replace fish meal protein with a plant protein. Since aquaculture products cannot utilise synthetic amino acids in sufficient quantities, more nitrogen metabolic waste is released into the environment, leading to environmental effects. Long-chain PUFAs, such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), are the main limiting fatty acids in terrestrial plant oils. Similarly, plant-based feed ingredients contain antinutrients that can change the structure of beneficial bacteria in the host's digestive system and negatively affect metabolism (Idenyi et al., 2022). Another problem with plant feeds is that approximately 70% of the phosphorus in them is bound to phytate, creating a potential for eutrophication and also reducing protein digestibility and increasing N excretion.

By-products as Aquaculture Feed

Fish Processing By-products

Every year, discards from world fisheries represent an amount equivalent to 25% of the total marine fisheries production. This amount exceeds 20 million tonnes worldwide and 5 million tonnes per year in the EU (Shahin et al., 2023). Approximately 25–35% of fish meal comes from fish processing by-products, and approximately 70% comes from fisheries. Collecting fish processing by-products is generally not considered economically viable due to logistical and technical constraints (Sarker, 2023).

The most important disposal method for these by-products is to use them in feed formulations for livestock and aquaculture species. According to EU Regulation 1069/2009, fish and aquaculture by-products are classified as Category 3 by-products, which are permitted to be included in animal diets to contribute responsibly to environmental sustainability and public health (Gasco et al., 2020). Discarded fishing by-products can be used in the production of FMFO (Li et al., 2019). *Enzymatic hydrolysis* of fishery waste is another technique for processing waste into fish protein hydrolysates (Gasco et al., 2020).

In a study (Warwas, 2023), three different fish processing by-products (fillets and trimmings) were used in rainbow trout feeds without separating the fat and protein fractions. The results showed that whether the by-products could be used as direct ingredients depends on storage conditions and processing. The inclusion of 50% fresh anchovy trimmings in the feed resulted in increased growth, improved feed intake, and maintained intestinal health. However, there are also disadvantages of using these by-products such as the protein and essential amino acid values, hygiene problems, shelf life of the product, and the prohibition imposed by the EU [Regulation (EC) No. 1069/2009, preventing the feeding of these by-products to the same aquaculture species (Gasco et al., 2020).

Food Waste

Food waste can also be used as a protein source in aquaculture feed production (Shahin et al., 2023). Food waste includes raw and cooked food materials, as well as recycled food residues. It is estimated that approximately 1.5 billion tons of human food residues, equivalent to one-third of the total annual human food production, are generated annually. Although not suitable for all aquaculture species, these food wastes have the potential to be used for some omnivorous species, such as tilapia (Nasser et al., 2018), and other low-trophic-level species, such as grass carp and mullet (Mo et al., 2014). However, as part of the 'precautionary' principle applied in EU Food Safety Policy, the use of food waste for food fish or growing insects is not allowed (Fowles & Nansen, 2020).

Single-cell Organisms/Proteins

Microorganisms, including microalgae, seaweed (macroalgae), yeasts, fungi, bacteria, and other alternative components, hold significant potential in aquaculture feeds due to their protein/amino acids, lipids, or omega-3 sources. With the increasing use of these microorganisms in aquaculture, together with technological innovations, it will also be possible to reduce the environmental footprint of aquaculture feeds (Sarker, 2023). These organisms can be considered a sustainable feed source because they grow rapidly, use very little freshwater, and do not require any agricultural land for their reproduction (Albrektsen et al., 2022).

Microalgae (Phytoplankton)

In aquaculture, microalgae play important roles due to both their effects on the aquatic environment and their role as a nutrient source (Wu & HU, 2023). Microalgae species constitute less than 1% of the Earth's photosynthetic biomass, yet they contribute to approximately 50% of the global biogenic fixation of carbon (Field et al., 1998). This is because the global population of phytoplankton is renewed on average every 2 to 6 days (Behrenfeld et al., 2006). In addition, microalgae are rich in omega-3 PUFAs, carotenoids, essential amino acids, β-1–3-glucan, minerals, and vitamins.

Microalgae protein and oil also have the potential to replace FMFO in aquaculture feeds. The crude protein content in microalgae ranges from 50% to 70% (Nagappan et al., 2021; Ma & Hu, 2023). Since microalgae can synthesise all amino acids de novo, their amino acid profiles were well balanced for aquatic animal feeds (Becker et al., 2013). The total lipid content of microalgae can reach up to 45-60% in dry cell weight (Ahmad et al., 2022). Microalgae can synthesise de novo omega-3 fatty acids, which can also meet the essential fatty acid requirements of aquaculture.

With the advent of industrial-scale microalgae production, their use in aquaculture feeds has accelerated. Among marine microalgae, *Nannochloropsis oculata*, *Isochrysis sp*., and *Schizochytrium sp.* are considered promising candidates for use in aquaculture feeds. It is stated that *Isochrysis sp.* microalgae can be a good alternative to FMFO in rainbow trout diets and can be used as omega-3 and DHA supplements in diets (Sarker et al., 2020). Recently, some aquaculture feed companies have begun producing DHA-rich oil from *Schizochytrium* sp. for use in salmon feed (Tocher et al., 2020). The current extremely high production cost of microalgae prevents their widespread use in aquaculture today (Nagappan et al., 2021).

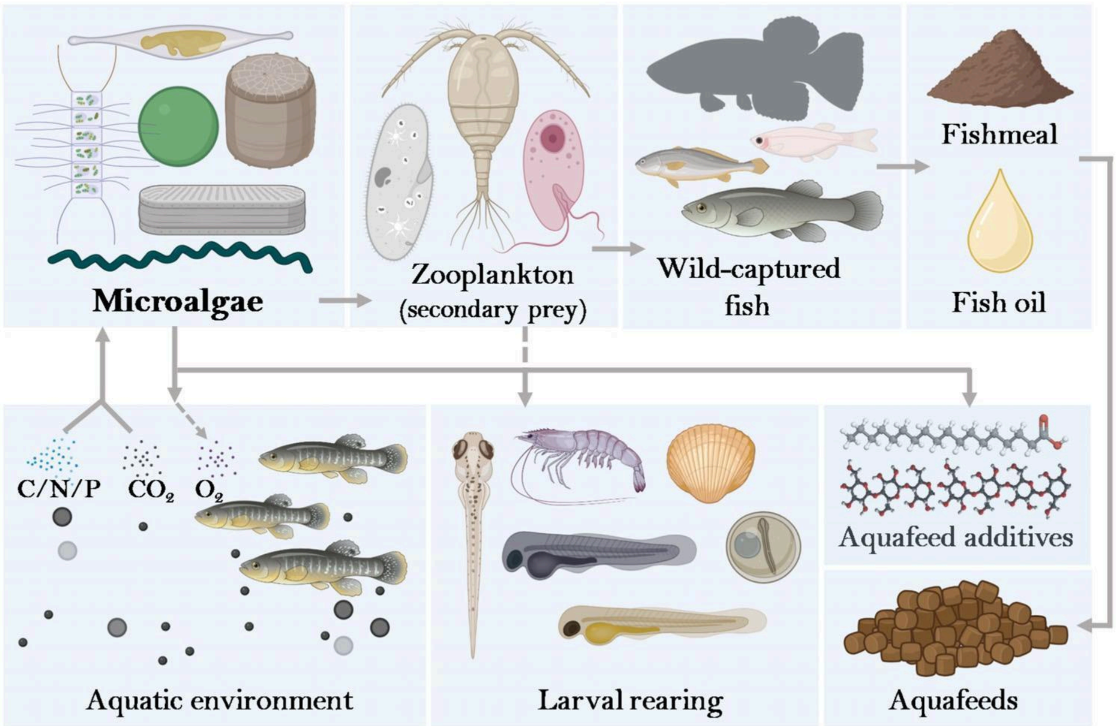

Figure 4.2. Roles of microalgae associated with aquaculture (Biorender.com (Wu & Hu, 2023)

Seaweed (Macroalgae)

Almost half of global seaweed (i.e., macroalgae) aquaculture production is worth over 11 billion US dollars. Today, more than 99% of seaweed farming is conducted in Asia, with significant growth in Africa (FAO, 2020). The majority of seaweed produced is Japanese kelp (Japanese wakame) and is used for human consumption.

In recent years, seaweed has gained importance due to its bioremediation capabilities, which provide a highly sustainable production method. The nutrient content of seaweed varies depending on the type of seaweed, such as red, green, and brown, as well as the season, with protein content ranging from 6% to 38% in red seaweed, 3% to 35% in green seaweed, and 2% to 17% in brown seaweed. Lipid levels are also reported to be in the ranges of <1–13%, <1–3%, and <1–10%, respectively (Nagappan et al., 2021). The majority of species have proteins rich in essential amino acids and contain high amounts of essential omega-3 HUFAs and PUFAs. Carbohydrate content is usually the most significant component (15–65%), depending on the species (Nagappan et al., 2021). The amount of crude fibre, that is, polysaccharide, is between 25–75% of its dry weight and cannot be easily digested by carnivorous species.

In general, it is stated that when whole seaweed is added to fish feeds at a low rate (<10%) instead of fish meal, there are improvements in the growth performance and pigmentation of fish (Ragaza et al., 2021). However, when it is used above 10%, growth performance and nutrient digestibility are negatively affected (Qiu et al., 2018). For seaweed to replace fish meal as an alternative source, it must undergo biorefining to isolate and enrich its protein content (Aasen et al., 2022). Fermentation is also suggested as another promising biorefining process for seaweed (Ang et al., 2021). These applicable processes are still under development, and the current EU regulations (EU Regulation 68/2013) only permit the use of seaweed biomass produced by drying and milling as a feed ingredient without specific approval.

Yeasts

Yeasts are considered an alternative feed source for aquaculture due to their high crude protein (30–60%) content. In aquaculture feeds, mainly *Saccharomyces cerevisiae*, various *Aspergillus* and *Fusarium venenatum*, as well as other strains such as *Candida utilis*, *Candida*, *Hansenula*, *Pichia*, *Torulopsis*, and *Kluyveromyces marxianus* can be used as protein components (Jones et al., 2020; Glencross et al., 2020). Yeast, mostly *Saccharomyces cerevisiae*, has shown positive results by producing beneficial immunostimulatory activity, mostly when partially replacing fish meal in salmon diets. Marine yeast (*C. sake*) contains 55% protein and significant levels of omega-3 fatty acids. In addition, the digestibility of *C. sake* in rainbow trout is also high and can be used in diet formulations up to 20% of the total content without causing adverse effects (Warwas, 2023).

Bacteria

Bacteria have the advantage of growing rapidly on organic substrates such as methane, methanol, carbon dioxide, hydrogen, and sugars (Matassa et al., 2020). Some bacterial strains can be used to produce very high crude protein contents (approximately 60% to 82% of dry cell weight) and essential amino acid levels (Ritala et al., 2016). A bacterial meal contains up to 80% crude protein (average = 60%) and approximately 10% fat, similar to fishmeal (Albrektsen et al., 2022). Recently, the inclusion of purple non-sulphur bacteria such as *Rhodopseudomonas palustris* and *Rhodobacter capsulatus*, a new emerging microbial protein source, has been found to improve growth performance, feed conversion ratio, and resistance to disease and stress in shrimp (Alloul et al., 2021). Furthermore, these purple phototrophic bacteria produced using wastewater can be used in amounts of up to 66% of fish meal in sea bass diets without any adverse effects on fish performance (Delamare-Deboutteville et al., 2019).

Although bacterial proteins are attractive for future aquaculture feeds, they face challenges such as high production costs and limited global adoption as fish feed (Sarker et al., 2023).

Insects in Aquaculture Feeding

The aquaculture feed industry is looking for alternatives to FMFO. In this context, insects can be a sustainable protein source for aquaculture using food waste. It has been determined that at least 16 of the approximately 1 million known insect species worldwide can serve as alternative protein sources in aquaculture (Guerreiro et al., 2020). Eight insect species have shown auspicious results (Alfiko et al., 2022). Among these, insect species such as silkworm (*Bombyx mori*), *Hermetia illucens*, *Musca domestica*, *Tenebrio molitor*, and crickets are the most important. It is stated that these insect species have a high crude protein ranging from 42–60% and are comparable to fish meal and soybean meal in terms of essential amino acids (Allegretti et al., 2017). The advantage of insect-based feeds is not only the amount of nutrients they contain, but also their reduced environmental impact, which is attributed to the high efficiency of waste conversion and the conversion of by-products into valuable feed resources.

In a study, it was determined that the seaweed fly (*Coelopa frigida*) can be grown in the wastewater of a seaweed farm producing brown seaweed and that the seaweed fly larvae can replace 40% of the fish meal in diet without causing adverse effects on growth and intestinal health of rainbow trout (Warwas, 2023). Diets created at different developmental stages of insects, such as larvae, pupae, and adults, have been tested in studies. Among these species, it has been determined that black soldier fly can be used as an insect meal, especially for rainbow trout (*Oncorhynchus mykiss*) and Atlantic salmon (*Salmo salar*) (Lock et al., 2018).

The European Commission has also approved the inclusion of insects in the diets of aquatic organisms (Regulation 2017/893/EC, 2017). As a result, many enterprises have been established in Europe for the cultivation of different insect species (Mancuso et al., 2019).

Low-trophic Marine Animals

Marine animals of particular interest due to their potential use as FMFO substitutes include *mussels, amphipods, and polychaetes*. These low-trophic organisms obtain their nutrients from primary producers such as phytoplankton, bacteria, and algae, as well as organic waste in the marine environment.

Mussels, such as green (*Perna viridis*) and blue (*Mytilus edulis*), are filter-feeding molluscs that currently account for approximately 56% of total marine animal aquaculture production (FAO, 2020). Mussels can be described as bioremediators that thrive in nutrient-rich environments, converting waste nutrients into protein without additional feed. They contain 50–70% protein and 5–16% lipids by dry weight, similar to fishmeal (Jusadi et al., 2021). The primary risk associated with using mussels as feed is their high accumulation of heavy metals (Rasidi et al., 2021).

Marine amphipods are an order of small, mostly benthic crustaceans with more than 10,000 recorded species. They have the potential to serve as an alternative live feed source for cephalopods, shrimp, and seahorses, as well as a partial replacement for fishmeal in fish and shellfish aquaculture (Ashour et al., 2021). Marine amphipods contain high levels of protein, PUFAs (EPA, DHA), and amino acids.

Polychaetes (i.e., annelid worms) are globally distributed, bottom-feeding bioremediators that consume algae and decaying or waste organic matter, converting them into valuable nutrients. Polychaetes are a significant source of food for commercially important fish and crustaceans (Khan et al., 2018). Traditionally, they are used as live fishery bait or as a high-quality food source for special diets (Pombo et al., 2020). They contain high amounts of protein (55–60% dry weight), lipids (12–28% dry weight), and PUFAs, accompanied by well-balanced amino acid, vitamin, and mineral profiles (Wang et al., 2019).

	Nutritional Composition	Sustainability			Consumer Perception	Commercial Feasibility
		Environmental	Economic	Social		
F & A by-products	↑	↑	↑	↑	↑	↑
Food wastes	↓	↑	↓	↓	↓	↓
Insects	↑	↑	↑	↑	↔	↑
SCO	↑	↑	↓	↑	↑	↓
Seaweed	↓	↑	↑	↑	↑	↑
Low-trophic marine animals	↑	↑	↑	↑	↑	↔

Fig.4.3. Qualitative potentiality assessment of alternative ingredients for aquaculture feeds (adapted from Shahin et al.,2023)

2.2. Reduction of Environmental Impact of Aquaculture Feed

In the aquaculture sector, feed accounts for approximately 40–60% of the costs, and protein (fish meal) is the most expensive nutrient. 70% of the FMFO used to meet the needs of aquatic organisms comes from capture fishing. This situation places significant pressure on fisheries and negatively impacts their sustainability.

2.2.1. Aquaculture and Sustainability Issues

Aquaculture and sustainability issues can be categorized into three main areas: economic, environmental, and social sustainability (Odeja, 2021). The key strategies to measure nutritional and environmental sustainability in aquaculture can be based on three main criteria (Sarker et al., 2023)

1. *Digestibility of Feed Ingredients:* The digestibility of aquaculture feed ingredients is an important parameter for formulating economically viable and environmentally sustainable feeds. It is necessary to determine the digestibility of ingredients. Thus, feed costs, nutrient pollution such as phosphorus and nitrogen eutrophication emissions, can be reduced, and feed conversion rates can be improved.
2. *Feed Conversion Ratio (FCR)*: The economic advantage of sustainable feed production using alternative ingredients is mainly due to the lower FCR. The FCR is a good indicator of the environmental performance of aquaculture as it indicates the potential negative consequences of phosphorus and nitrogen waste outputs in the aquatic environment, such as eutrophication, GHGs, loss of biodiversity, and impacts on other ecosystems. However, the FCRs of aquaculture have decreased from approximately 3 to about 1.35 in aquaculture and from approximately 2–2.25 to about 0.9–1.2 in salmon farming, mainly due to improvements in feed formulations since 1970 (Sarker et al., 2023).
3. *Life Cycle Assessment (LCA) for Ecological Impact Measures:* LCA can be used to measure the environmental impacts of food systems, including aquaculture. Environmental impact categories can be assessed, including sustainable feed development, the use of alternative ingredients, efficient use of resources such as land, water, and fertilizer, global warming emissions, eutrophication emissions, biodiversity loss, and negative externalities like ocean acidification (Sarker et al., 2011). It is necessary to see the LCA impacts of high-quality new protein and fat production on FMFO in feeds.

Sustainability of Aqua-feed Production

Feed production accounts for the most significant part of both the environmental and economic footprint of modern aquaculture operations; therefore, sustainable aquaculture can only be achieved by using sustainable feed (Warwas, 2023). The European Commission's new guidelines include aquaculture as part of the EU's Farm to Fork strategy, which aims to accelerate the transition to a sustainable European food system. The strategy highlights the potential of sustainable aquaculture to provide food and feed with a low carbon footprint, while also creating economic opportunities and jobs (Odeja, 2021). In addition, the Commission recommends that feed manufacturers limit their reliance on FMFO from wild stocks and instead use alternative protein ingredients such as algae, insects, or waste from other industries. However, today, most of the commercial aquaculture feeds consist of FMFO. It is expected that the demand for FMFO could exceed the supply of smaller fish as early as 2037. This means that industrial feed is not sustainable on a commercial scale in the long term (Smárason, 2023). To protect marine ecosystems and reduce ocean resource depletion, aquaculture feed must be sustainable. While the main alternative feed ingredients in aquaculture include soy- and corn-based feeds, their production has been criticised because they are unsustainable and have poor digestibility. Therefore, the circular bioeconomy is gaining importance for the future of the aquaculture feed industry (Bunting, 2021).

3. Feed Management Practices

3.1. Precision Feeding Techniques

Innovative approaches, such as flexible ingredient formulations, enzymes, optimised microbiomes, and genetics, are playing a key role in bringing many aquaculture species closer to precision nutrition. Precision feeding involves formulating feed to unlock the potential of fish and crustaceans' DNA, microbiomes, and metabolic responses, thereby preventing disease and promoting efficient growth (Howell, 2022).

Microbiome-based Feeding

The microbiome is still something of a 'black box' in aquaculture nutrition. Over the last five years, there has been a significant increase in scientific studies examining the gut microbiome in the context of aquaculture. Emerging genetic sequencing technologies have enabled the mapping of microbial communities living in the guts of over 20 species of farmed fish. In the future, profiling the membership of gut microbial communities, in particular their functions or functional outcomes in the gut, will be an area for further investigation. This shift will shed light on ongoing research questions such as the link between microbial diversity and metabolite production. It will allow the industry to establish baseline metrics for gut health. Focusing on the function of the gut microbiome will also lead to improvements in nutrient digestibility and fish performance (Howell, 2022). Within the scope of the intersection of genetics and nutrition, genetic selection in aquaculture now targets not only disease resistance and improved growth, but also nutrient utilisation. This will make precise feeding techniques based on their genetic characteristics even more important.

Net Energy-based Feed Formulation

The next phase in precision nutrition will go beyond replacing FMFO from fisheries with alternatives and will involve using all feed ingredients in flexible and sustainable ways. In aquaculture, feed formulation is mainly based on digestible energy (DE). In this system, it is assumed that energy is used in a standard way for growth. The main reason for this is that it is difficult to accurately measure non-faecal energy loss in fish compared to terrestrial animals. Therefore, it can be determined that using metabolizable energy (ME) and net energy (NE) values instead of DE values for aquaculture feeds will provide significant advantages (Groot et al., 2021). To make this shift and use feed ingredients more sustainably, the industry could adopt feed formulations that focus on *net energy* rather than *digestible energy*. The key difference between the two systems is that the digestible energy system assumes that all dietary macronutrients are used in the same way by fish. In contrast, the net energy system assumes that proteins, fats, and carbohydrates in fish diets are used differently. In recent years, aquaculture nutritionists have made significant progress in developing net energy models for various fish species (Howell, 2022).

Since the environmental impact of feeds is primarily determined by their ingredients, there is an opportunity to reduce the environmental impact of aquaculture by formulating feeds with lower environmental impacts (Wilfart et al., 2023). In some studies, the potential environmental impacts of feeds have been considered in feed formulation (Mackenzie et al., 2016). Formulating feeds according to environmental and economic criteria can be seen as an innovative approach to address the current challenges of animal production (Garcia-Launay et al., 2018).

3.1.3. Multi-objective (MO) Feed Formulation

MO feed formulation, which aims to strike a balance between lower costs and reduced environmental impacts, can be seen as a promising solution to mitigate the environmental footprint of aquaculture production (Wilfart et al., 2023). Recently, Garcia-Launay et al. (2018) developed a *multi-objective (MO) formulation* that uses the constraints of the least-cost formulation (nutrients and feed ingredient addition rates) and calculates an MO function that includes both feed cost and environmental impact indicators obtained by LCA (i.e., climate change, non-renewable energy use, P demand, land occupation). However, fish growth can be significantly affected by the type of raw feed ingredients. For example, replacing all FMFO with raw plant ingredients reduced rainbow trout growth by 30% (Lazzarotto et al., 2018). A multi-objective feed formulation method has been developed that considers both the cost and environmental impacts (estimated by LCA) of the feed mixture. In the first step, the least-cost formulation provides a baseline for feed cost and potential impacts per kg of feed. In the second, the minimised MO function includes normalised values of feed cost and impacts climate change, P demand, non-renewable energy demand, and land occupation. An additional factor weighs the relative influence of economic and environmental objectives.

The potential of the MO feed preparation method was evaluated using two feed formulation scenarios for pigs, broilers, and young bulls. Compared to the basic feeds, MO formulated feeds were found to have lower environmental impacts (from –2 to –48%) and a moderately higher cost (1–7%) in both scenarios studied, except for land occupation of broiler feeds. The developed method complements other strategies and should be investigated in the future to optimise the entire animal production system to significantly reduce the associated impacts (Garcia-Launay et al., 2018). The MO formulation can be used as a valuable tool to reduce the environmental footprint of aquaculture production without compromising animal performance or necessarily increasing production costs (Wilfart et al., 2023).

3.2. Pre-treatment Technologies and Fermented Feeds for Aquaculture Feeding

Plant feeds are often used as the primary protein source in aquaculture feeds due to their wide availability and low cost. However, they usually contain high levels of non-starch polysaccharides (NSPs), which limit their use in aquaculture feeds, especially for carnivorous fish. They also have low palatability, unbalanced amino acid profiles, and contain antinutritional factors (ANFs), which limit their use and increase waste production. Therefore, efficient utilisation of these ingredients by aquaculture is of great interest.

Fermentation of feeds is a cost-effective technological process that can reduce ANFs levels while improving nutrient digestibility and the production of various bioactive compounds, increasing the nutritional value of feed ingredients in aquaculture feeds. Solid-state fermentation is primarily characterised by the use of microorganisms, such as filamentous fungi, that efficiently penetrate the substrate through low free water and hyphal growth (Šelo et al., 2021). Therefore, it can be fermented with microorganisms such as *Aspergillus niger*, *Aspergillus oryzae*, *Saccharomyces cerevisiae, Bacillus subtilis,* and *Bacillus licheniformis*, and used in either a solid-state or wet-state fermentation. These organisms can affect feeds by producing various enzymes, including phytases, lipases, proteases, and carbohydrases such as cellulases and xylanases. Fungi, in particular, are defined as enriching lignocellulosic materials with microbial proteins and enzymes. In this way, the crude fibre content is reduced. In contrast, crude protein, protein solubility, and protein and fibre digestibility are increased (Godoy et al., 2018), thereby enhancing the nutritional value of plant feeds for use in aquaculture. If solid-state fermented feed is to be formed, the fermented mixture is left to dry in a temperature and environment that will not damage the nutrients (Vieira et al., 2023; Zengin et al., 2022).

4. Mitigating The Effects of Ocean Acidification

The oceans are natural carbonate buffer systems that act as a carbon sink in the environment, which is significantly larger than the atmospheric and terrestrial carbon content. The ocean is an excellent buffer to neutralise small changes in its composition. As more atmospheric CO_2 is dissolved in ocean water, carbon is released from the ocean carbon sink, making the oceans more acidic (Ebeneezar et al., 2023). The oceans absorb CO_2 from the atmosphere, acting as a buffer to atmospheric CO_2 levels. If oceans absorb more CO_2, this leads to decreases in seawater pH, carbonate ion concentrations, and calcium carbonate (CaCO3) mineral concentrations, creating a situation known as 'ocean acidification' **(**Reid et al., 2019).

Since simultaneous increases in CO_2 (decreased pH and aragonite saturation) and temperature will occur, along with changes in salinity and, in some cases, decreased oxygen levels (Boyd et al., 2015). Ocean acidification and temperature are interrelated. Given the potential for negative synergies, increasing temperature has been considered the 'evil twin' of ocean acidification. Increasing acidity levels in seawater also negatively affect the physiology and metabolism of aquatic species by disrupting intercellular transport mechanisms. It has been reported that larvae exposed to lower pH seawater exhibit lower gastric pH, resulting in reduced digestive efficiency and increased food consumption (Stumpp et al., 2013). Warm climatic conditions would also deplete oxygen in the water, resulting in a reduction of phytoplankton. Plankton play an important role in moderating the world's climate by absorbing CO_2 emissions. Phytoplankton account for approximately half of global photosynthesis and play a crucial role in mitigating global warming (Huertas et al., 2011).

4.1. Buffering Agents to Mitigate Ocean Acidification

Incorporating buffering agents in feed formulations helps counteract the effects of ocean acidification on the digestive physiology of aquaculture species. Buffering agents in feed formulations neutralize or stabilise the pH in the digestive tract, providing optimal conditions for nutrient absorption.

Buffering agents are:

- *Algae* reduce ocean acidification and offset emissions. *Seaweed*, including kelp, also reduces ocean acidification by removing carbon dioxide from the water and acts as a local 'buffering' agent that benefits many marine species. Seaweed also produces dissolved oxygen, reducing the spread of 'dead zones' in the water. Large-scale seaweed farming is also being explored as a means to remove and sequester carbon dioxide from the deep ocean (NOAA Fisheries, 2022).
- *Inorganic buffers*: These are usually compounds such as sodium bicarbonate ($NaHCO_3$), calcium carbonate ($CaCO_3$), or magnesium hydroxide ($Mg(OH)_2$), which are commonly used to maintain pH stability.
- *Organic buffers*: Compounds such as citric acid salts (such as sodium citrate) or organic acids (such as formic or lactic acids) are also potential buffering agents. They tend to be more specific in their buffering capacity and may also support intestinal health by affecting microbial communities.
- *Phytochemicals and plant-based buffers*: Some plants produce compounds that can naturally buffer pH levels and provide additional benefits such as antioxidant properties or anti-inflammatory effects. These may be useful in organic or sustainable aquaculture systems.

In conclusion, incorporating buffering agents into aquaculture feed formulations presents a promising strategy for mitigating the effects of ocean acidification. This approach not only supports the health and growth of farmed species but also increases the resilience of aquaculture systems to climate change.

4.2. Nutritional Strategies to Mitigate Ocean Acidification

In aquaculture, improving resilience to acidic conditions is a crucial issue, particularly in the context of ocean acidification, to develop effective feed and feeding strategies for sustainable aquaculture (Parker et al., 2024). This can have a negative impact on marine life, particularly species that rely on stable pH levels for optimal growth, development, and health, such as fish, shellfish, and crustaceans. Feed and feeding strategies that increase endurance, improve health, and increase stress resistance should be developed.

Some feeding strategies to mitigate acidification are:

1. **Use of minerals.** Under acidic conditions, the availability of calcium and magnesium in water may decrease, and these minerals are necessary for maintaining the integrity of shells in molluscs and crustaceans. Low pH can affect the solubility of trace elements in water, so adding them to feeds can support the health of fish and shellfish. Therefore, adding highly bioavailable forms of calcium and magnesium to feeds can help these species maintain their shells well and grow properly.

2. **Use of vitamins.** Under stress conditions, such as acidification, fish and shellfish may experience oxidative stress, which can be mitigated by adequately supplementing feeds with vitamin C. Vitamin E is a powerful antioxidant that helps protect cells from oxidative damage caused by environmental stressors, including acidification. B vitamins, such as B_1 (thiamine), B_2 (riboflavin), and B_{12} (cobalamin), play important roles in energy metabolism, nervous system function, and overall stress tolerance.

3. **Essential Amino Acids and Fatty Acids**. Under stress conditions caused by ocean acidification, the metabolism and protein synthesis in the bodies of aquaculture animals can change. Adding amino acids such as methionine, lysine, and threonine to the diet can help maintain growth, tissue repair, and immune responses under these stress conditions, which are essential for reducing inflammation, supporting immune function, and promoting overall growth. Supplementing aquaculture diets with EPA and DHA may help alleviate some of the adverse physiological effects of acidification.

4. **Probiotics and Prebiotics.** Adding beneficial direct-fed microorganisms may be especially important in acidified waters, where the stress of pH changes can lead to gut microbiome imbalances or weakened immunity. Prebiotics can also improve digestion and overall health by feeding beneficial bacteria in the gut. By promoting healthy microbiomes, aquaculture species may be better able to cope with environmental stress.

5. **Antioxidants and Phytochemicals.** In acidic environments, reactive oxygen species tend to accumulate, leading to oxidative stress. Adding natural antioxidants, such as carotenoids and polyphenols, to feeds can help mitigate oxidative damage and increase resilience.

5. Enhancing Feed Efficiency and Digestibility

5.1. Extrusion Processing

Extrusion processing is a method applied to cook and pasteurise feed components or feed by exposing them to high temperatures and pressures for a short time, thus eliminating all ANFs and increasing feed consumption, nutrient digestibility, and, consequently, fish growth. Feed ingredients extruded in this way promote higher lipid levels in the feed, gelatinisation of starch, and increases in protein and energy digestibility of feed. Extrusion is also essential in aquaculture production as it positively affects physical properties such as reduced fineness, buoyancy, and sinking.

Utilising Enzyme Additives

Utilising enzyme additives to improve the digestibility of feed ingredients and enhance nutrient absorption, thereby maximising growth and health under changing environmental conditions, is crucial for aquaculture feeding. In particular, adding enzymes to extruded fish feeds to enhance phosphorus, carbohydrate, and protein digestibility can improve environmental sustainability by reducing the release of compounds from the fish into the water. In this context, it is also important to develop feeds that maintain their digestibility despite changing water temperatures, which can occur due to high or low water temperatures associated with global warming.

Because as the melting points of the fatty acids in the feed increase in cold water conditions, digestibility decreases, which negatively affects FCR. This effect is much more pronounced in cold water temperatures than in warm waters. Therefore, it is necessary to increase general fat digestibility by lipases in particular (Howell, 2022). Protease enzymes can stimulate endogenous peptidases by improving protein digestibility and hydrolysing proteinaceous antinutrients such as lectins, trypsin inhibitors, antigenic proteins, and antinutritional allergenic proteins, including glycinin, β-conglycinin, and kafrin (Cowieson, 2008). The use of plant-based feeds rich in NSPs in the digestive tract of fish, enzymes such as xylanases, glucanases, and cellulases, can increase the digestibility and utilisation of nutrients provided by alternative ingredients (Sarker, 2023).

5.2. Functional Feed Additives

Functional feed additives are feed additives that are incorporated into feed formulations to provide the basic nutritional requirements of conventional feeds as well as to improve the growth and health of aquaculture. Their use in aquaculture feed formulation provides benefits such as improving intestinal health and beneficial intestinal bacteria, increasing enzyme production, and stimulating appetite, which in turn leads to improved growth performance. Additionally, these feed additives can mitigate the negative environmental impact of aquaculture by enhancing water quality and promoting the use of alternative proteins in aquaculture feed (Onomu & Okuthe, 2024).

The use of terrestrial, plant-based protein as a partial or complete substitute for fishmeal requires feed supplements. Antibiotics and chemotherapeutics used in aquaculture can lead to the development of antibiotic-resistant bacterial strains and the elimination of unintended natural microorganisms, as well as product-based antibiotic residue problems for humans. On the other hand, probiotics, prebiotics, and phytogenics can be used as functional feed additives to prevent or reduce disease and enhance host immunity (Van Doan et al., 2020). However, there is less information available on functional feed additives in aquaculture than in other animals, especially regarding their relationship to the sustainability of aquaculture (Onomu & Okuthe, 2024).

The sustainability roles of functional feed additives based on their five main effects on aquaculture:

1. Increased feed utilisation
2. Enhanced sustainable resource utilisation
3. Enhanced disease resistance and immunity
4. Increased parasitic resistance
5. **Improved water quality**

Probiotics (Direct Feed Microbials: DFMs), Prebiotics, and Symbiotics

Beneficial microorganisms and prebiotic compounds in feeds support gut health, boost immunity, and improve overall feed efficiency in the face of stressors associated with global warming.

Probiotics

Probiotics have been defined as live feed additives that have beneficial effects by improving the intestinal microbial balance in host animals (Fuller, 1989). These substances contribute to growth or development by increasing feed consumption, feed utilisation, or affecting the immune system in animals (Demir et al., 2003). Probiotics are a globally accepted functional feed additive in aquaculture feed. Although there are many definitions of probiotics, such as 'live microorganisms that when administered in adequate amounts confer a health benefit on the host', these definitions are suitable for terrestrial animals and humans but not for aquatic animals. This is because aquatic animals and microorganisms coexist in the same aquatic environment. In aquatic animals, the interaction between microorganisms (including probiotics) and the host occurs not only in the intestinal tract but also in the surrounding water (Onomu & Okuthe, 2024).

Bacterial pathogens are becoming increasingly resistant to antimicrobial drugs, pesticides, and disinfectants used in aquatic disease control. For this reason, the study of probiotics in aquaculture is in high demand to ensure eco-friendly, sustainable aquaculture as an alternative to antibiotics. Unfortunately, plant-based ingredients can have several adverse effects on aquaculture nutrition (Nielsen et al., 2022). Probiotics stabilise the microbial population of the fish's gastrointestinal tract through the elimination of pathogenic microbes and increased digestibility and bioavailability of nutrients (Oscar et al., 2020).

Bacteria, yeast, and algae are extensively utilised as probiotics in aquaculture. The effects of probiotics can be classified into two groups according to the aim of the treatment (Nathanailides et al., 2021):

- Fish growth and welfare parameters, including effects on fish growth and feed conversion parameters, gut microbiota and anatomy, immunity, and resistance to pathogens.
- Environmental parameters, including fishponds and/or tanks (water quality, diversity of aquatic microbiota).

A number of probiotic microorganisms have been isolated and evaluated for use in aquaculture to prevent and control infectious diseases in aquaculture species. Results of two studies using two commercial probiotics to evaluate the effects of probiotics on female rainbow trout broodstock

(Akbari Nargesi et al., 2020) and *Nile tilapia* (*Oreochromis niloticus*) (El-Kady et al., 2022) have indicated that probiotics can improve reproductive parameters, decrease total ammonia nitrogen and ammonia, and increase growth performance and feed utilisation compared to the control.

Prebiotics and symbiotics

Prebiotics are non-digestible feed additives, mainly consisting of oligosaccharides that stimulate and metabolise beneficial microorganisms in the gastrointestinal tract, while improving the health of the host (Bozkurt et al., 2014). In order for a feed additive to be categorised as a prebiotic, it must reach the colon without being digested, be resistant to gastric acidity, be hydrolysed by digestive enzymes, and be absorbed by the gastrointestinal tract (Davani-Davari et al., 2019). The usefulness of prebiotics as feed additives is related to the by-products obtained during fermentation by bacteria in the intestine. The main types of prebiotics used in aquaculture are mannan oligosaccharide (MOS), fructooligosaccharides (FOS), galactooligosaccharides (GOS), arabinoxylan oligosaccharides (AXOS), inulin, and β-glucan.

Probiotics mixed with various probiotics strains or prebiotics (*symbiotics)* result in better benefits in terms of growth and health compared to probiotics/prebiotics alone. This is because the use of multiple strains or synbiotics is considered to complement each other, thus expanding their spectrum of effects on the host (Puvanasundram et al., 2021). Widanarni et al. (2019) showed that dietary mannan oligosaccharides (MOS) supplementation through *Artemia* sp. could significantly improve postlarval digestive enzyme activities, growth, survival, and resistance to *Vibrio harveyi* infection. Dietary supplementation of 1.5 g kg^{-1} β-1.3 glucan and fructooligosaccharides in Pacific white shrimp (*Litopenaeus vannamei*) may be effective in enhancing growth performance and antioxidant activities, and improving nonspecific immunity and disease resistance (Eissa et al., 2023).

Phytogenics

Phytogenics are a group of feed additives derived from leaves, stems, roots, seeds, tubers, fruits, shrubs, and spices. Phytogenics generally stimulate appetite, strengthen beneficial intestinal bacteria, and are used in farm animals for their antioxidant, antimicrobial, anticarcinogenic, analgesic, and antiparasitic effects. Since they contain active compounds, they can also have toxic effects. Their properties and effectiveness are highly variable and vary according to the plant part used, extraction technique, concentration, harvest season, and geographical location (Onomu & Okuthe, 2024).

In a study, two phytogenic feed additives, one rich in carvacrol and the other rich in thymol, improved feed efficiency compared to the control diet and increased antioxidant protective capacities in rainbow trout (*Oncorhynchus mykiss*) (Giannenas et al., 2012). It also regulated intestinal microbial communities by negatively affecting the total number of anaerobes. A study by Abdel-Latif et al. (2020) examined the application of dietary thyme essential oil (OEO) to fingerling carp (*Cyprinus carpio L.*). When comparing fish fed OEO to the control group, they showed a notable improvement in intestinal morphometric parameters. Ghafarifarsani et al. (2022) examined the effects of quercetin, thyme essential oil, and vitamin C on the diets of common carp (*Cyprinus carpio*). They found that fish fed quercetin diets had higher levels of antioxidants in their serum and liver, including catalase, superoxide dismutase, glutathione peroxidase, and glutathione reductase, after the 60-day feeding trial. The effects of marjoram extract on the common carp fish, *Cyprinus carpio*, were examined by Yousefi et al. (2021). The maximum final weight, weight gain, and specific growth rate, as well as the lowest FCR, were seen when 200 mg kg^{-1} of marjoram extract was added to the diet.

Antistress feed additives

The most important effect of climate change is the stress it will create in aquaculture due to environmental factors. In recent years, studies on stress reduction in fish have been increasing. In addition to developing new technologies to improve the environmental conditions of aquaculture, it is essential to incorporate beneficial additives into their feeds to mitigate the stress response to typical stress factors. The use of various additives in fish diets to mitigate stress responses has been extensively studied. In these studies, immunological, nutritional, and metabolic changes, always related to endocrine processes, have been reported. The biochemical nature and physiological functionality of these feed additives significantly influence the stress response, as they can act as neurotransmitters or hormone precursors, energy substrates, cofactors, and other essential elements, which in turn create multi-system and multi-organ responses (Herrera et al., 2019).

Some of the feed additives to reduce the physiological impact of stress are lipids and fatty acids, vitamins, minerals, amino acids, nucleotides, prebiotics, and antioxidants. Ding et al. (2022) examined the impact of synthetic PUFAs in lowering the impact of temperature on corals. They found that both larval development and larval settlement were markedly enhanced in the diet supplement group, while superoxide dismutase, catalase, and death rates of stressed corals declined. Another study examined the potential immunomodulatory effects of *Astragalus membranaceus* (AM) and *Glycyrrhiza glabra* (licorice) on yellow perch (*Perca flavescens*), where stress parameter values were impacted (Elabd et al., 2016). Throughout the experiment, they reported that giving AM and licorice diets significantly improved growth performance, antioxidant, and immune response profiles – all of which are beneficial as natural stress relievers.

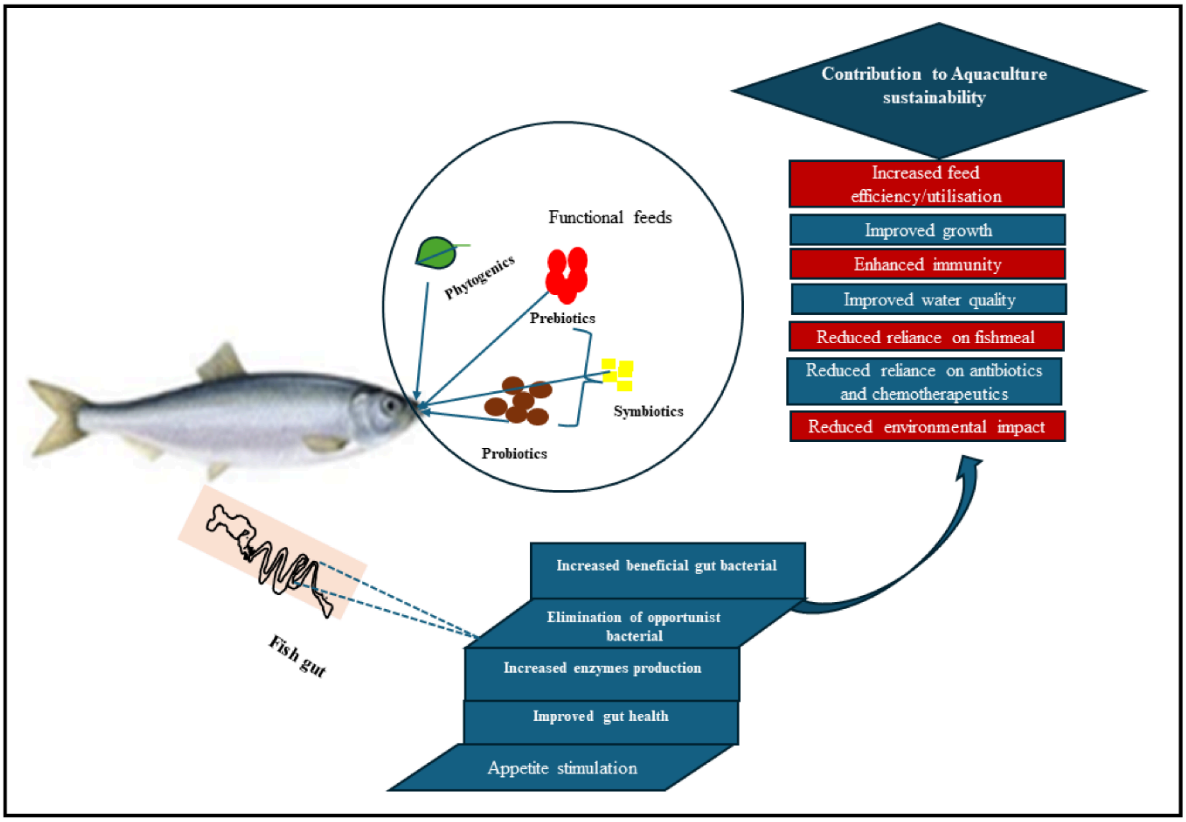

Figure 4.4. Effects of functional feed additives in aquaculture (adapted from Onomu & Okuthe, 2024)

Summary

Global warming can increase water temperatures, increasing metabolic rates of aquaculture species, necessitating changes in feed formulation to meet increased nutrient demands. Adjustments in protein, lipid, and carbohydrate ratios in feeds should be made to adapt to changing metabolic needs and ensure optimum growth and health of the species. As fish stocks used for fishmeal and fish oil are affected by climate change, alternative protein sources such as insect meal, algae, and plant-based proteins are becoming important for sustainable aquaculture feed. Innovations in feed composition are needed to reduce the ecological footprint, such as using waste-sourced ingredients and optimising feed conversion ratios. The application of advanced feeding technologies, such as automated feeders and real-time monitoring, is important to optimise feed distribution, reduce waste, and ensure efficient use of resources. Feeding frequencies and amounts should be modified to match the changing appetite and growth rates of species under changing temperature conditions. Buffering agents should be added to feed formulations to help offset the effects of ocean acidification on the digestive physiology of aquaculture species. It is helpful to develop feed strategies that increase the resilience of aquaculture species to acidic conditions, such as including minerals and vitamins that support stress resistance. Using enzyme additives to improve the

digestibility of feed ingredients and enhance nutrient absorption is vital, thereby maximising growth and health in changing environmental conditions. Adding beneficial microorganisms and prebiotic compounds to feeds to support gut health, boost immunity, and increase overall feed efficiency in the face of global warming-related stressors will increase efficiency.

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Chapter 5. Effects of Global Warming on Diseases in Aquaculture and Protective Applications

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Introduction

Climate change is ongoing and it affects the aquatic environment (freshwater, marine or brackish ecosystems) by increasing water temperatures, alterations in water levels and flow regimes, eutrophication, acidification, changing nutrient loads, increasing ultraviolet (UV) light penetration, decreasing habitat and degradation, and increasing thermal stress and distribution of species.

Variations in the aquatic environment, such as temperature, salinity, and chronic stress of low dissolved oxygen levels, affect mucosal barriers, the epithelia, immune cells, and the internal environment (i.e., the body fluids, cells, tissues, and organs) on/in aquatic organisms. These lead to reduced immunocompetence in aquatic organisms, poor growth, and lower reproductive performance.

Climate change, which includes global warming, may also adversely affect energy reserves in fish, contributing to increased oxidative stress and decreased thermal tolerance (Woo & Iwama, 2019).

It has been estimated that for mankind to maintain its consumption of seafood at current levels, aquaculture needs to produce over 80 million tons (t) by 2030 in order to maintain current per capita consumption. Thus, aquaculture will need to produce an additional 30 million tons of seafood in less than a decade and a half. There is probably not enough land or suitable marine areas for this to occur without massive disruptions to multiple ecosystems. However, about 40% of all aquaculture production is lost to disease, as it is broadly defined below. So, by **simply removing or limiting disease impacts, mankind could almost meet seafood requirements without changing any land utilising practices** (Lucas et al., 2019).

Average global air temperature is predicted to increase by 0.5–1.5°C by 2030, and impacts are expected to accelerate beyond a global temperature increase of 1–2°C. Global Ocean temperature in the upper 100 m is projected to increase by 0.6–2.0°C by 2100. Thermal expansion of warming ocean water and melting of ice sheets and glaciers are very likely to cause an increase in global mean sea level of 10–35 cm by 2050. Climate change has also resulted in the increased frequency of extreme weather events, such as storms and droughts. By 2050, the costs of extreme weather could reach 1% of global GDP per year. About 20–35% of CO_2 emissions are taken up by oceans, leading to ocean acidification.

Global warming is increasing the prevalence and intensity of diseases. Elevated water temperatures can enhance the growth and reproduction rates of pathogens, leading to more frequent and severe disease outbreaks in aquaculture. Higher water temperatures accelerate the life cycles of many aquatic pathogens, increasing their prevalence and virulence. Bacteria, viruses, and parasites may become more aggressive or develop resistance to treatments. Many aquaculture species have narrow thermal tolerance ranges. Elevated temperatures can weaken their immune systems, making them more susceptible to infections and diseases. Warmer waters may allow tropical and subtropical pathogens to expand their range, exposing aquaculture species in temperate regions to new diseases.

Climate change threatens unique and vulnerable ecosystems like coral reefs. In terrestrial and freshwater ecosystems, climate change causes biodiversity losses and increased colonisation by invasive species. The combined effects of sea-level rise, coastal erosion, pollution, and ocean acidification threaten coastal ecosystems (Lucas et al., 2019).

The implications of climate change for aquaculture in the future are profound. As climate change results in increased frequency of droughts and extreme weather, disruptions to pond-based production can be expected. Furthermore, reduced crop yields and increased demand associated with population growth and economic growth will create scarcity and increase prices of commodity crops used to produce aquaculture feeds. Sea level rise and extreme weather will increase the vulnerability of aquaculture in the coastal zone, including coastal shrimp and fish ponds, shellfish rafts, and fish cages, especially in Asia with abundant aquaculture infrastructure.

Ocean acidification will challenge the sustainability of coastal bivalve shellfish aquaculture. Global climate change is likely to exacerbate aquaculture's susceptibility to disease events (Lucas et al., 2019).

Increased CO_2 levels lead to ocean acidification, which affects calcifying organisms like shellfish and corals. Acidic conditions weaken their shells and skeletons, making them more vulnerable to disease and environmental stress. Acidification can alter the composition and health of aquatic ecosystems, potentially impacting species that rely on these habitats, including those farmed in aquaculture systems.

Global warming can cause changes in salinity through altered precipitation patterns and increased freshwater runoff. Aquaculture species may experience osmotic stress, leading to higher disease susceptibility and reduced growth. Variations in salinity can affect the prevalence of specific pathogens and diseases, requiring adjustments in management practices.

Due to global warming, increased nutrient runoff from agriculture and urban areas can lead to eutrophication, causing algal blooms and hypoxic conditions. These changes degrade water quality and create environments conducive to disease outbreaks.

Global warming can cause harmful algal blooms (HABs). Some algal blooms produce toxins that can directly harm aquaculture species or create conditions that favour pathogenic organisms.

Extreme weather events, such as storms and floods, can cause physical damage to aquaculture infrastructure and lead to sudden changes in water quality. These stressors can weaken the health of aquatic species and increase their vulnerability to diseases.

Global warming can alter the distribution and diversity of aquatic pathogens. New or previously rare pathogens may become more common, posing new challenges for disease management in aquaculture.

Other climate change effects, such as hypoxia, acidification, and changes in salinity, can compound stress and further impair immune function.

Global warming can alter the life cycles and interactions between hosts and parasites, potentially leading to the emergence of new disease vectors and transmission routes. To adapt to the changing pathogen landscape, aquaculture operations must implement updated disease monitoring and management strategies.

1. Common Diseases and Their Impacts

1.1. Classification and Key Symptoms

Introduction to Aquaculture Diseases

Disease is the body's reaction to unfavourable factors of the external environment. As a result, the body's normal functioning is disrupted, and its ability to adapt is reduced. At the same time, the body's defensive functions are mobilised.

Diseases are characterised by certain clinical phenomena, symptoms, corresponding damage to the body's tissue structure, and disorders of their functions.

The Sneizko three rings, Venn diagram of the interactions between host (the aquaculture species), pathogen, and environment (Figure 5.1), illustrates the fact that, to occur, most infectious disease is a three‑way interaction needing all components:

- pathogen;
- host;
- environment.

A non-infectious disease is an interaction only between the host and the environment. The area of overlap between pathogen and host represents obligate pathogens: the most threatening group, as they do not need environmental stress to cause clinical disease (Lucas et al., 2019).

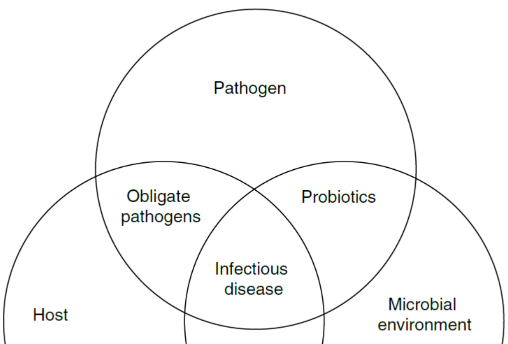


Figure 5.1. Modified Sneizko three-ring model depicting the interaction between host, pathogen, and the environment (Lucas et al., 2019).

Behavioural and Physical Abnormalities

Abnormal behaviour is often the first indication of an impending fish health problem. Professionals need to be familiar with the expected behaviour and appearance of the fish species. All behaviours, including feeding and swimming activities, and responses to sudden movement, must be carefully observed. The fish producer must learn to distinguish nuances in behaviour. Healthy fish display ‘normal’ behaviour. Table 5.1 lists abnormalities that may be observed when fish are sick. These signs will aid in diagnosing the cause of a problem (Timmons & Ebeling, 2013).

Table 5.1. Fish behavioural and physical signs for stress and sickness (Timmons & Ebeling, 2013)

Movement	Weak, erratic, or lethargic swimming Increased or decreased reaction to external stimuli such as noise or movement Scratching, flashing, or rubbing against tank walls or bottom Twitching, darting, spinning, or jumping out of the water Crowding near the influent water supply Swimming upside down Gasping at the water’s surface
Feeding	Not feeding Reduced feeding (detected by growth curves as well as observation)
Breathing	Decreased rate of opercular movement Increased rate of opercular movement
Physical Condition	Visible lesions or sores Cloudy eyes Protruding eyes Gills swollen, white, pink, or pale red, eroded, puffy, bloody, brown Scale loss

	Swollen abdomen Excess mucus on the skin and/or gills (also, check for excess mucus on tank screens) Spots or fungus on skin Unusual colorations on body surface, including red swollen areas, grey or yellow lesions Flared opercula (gill covers) Frayed fins or tail Bubbles in eyes or on skin

Fish raised in aquaculture systems face various types of stressors that can be broadly classified into abiotic and biotic stressors. Effects of abiotic stressors in cultured fishes are challenging to estimate (Figure 5.2). Some of the biotic factors can be readily controlled, and a careful manipulation of certain biotic factors may successfully prevent or at least minimise disease loss in aquaculture (Jeney, 2017).

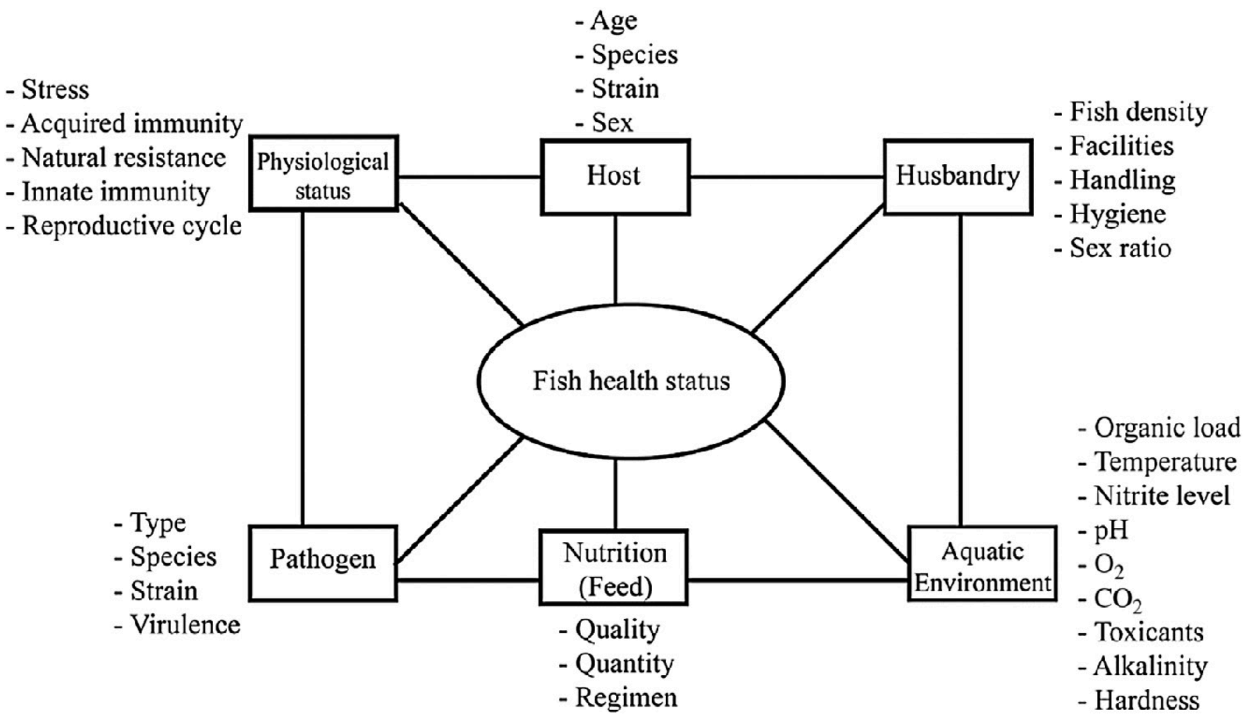


Figure 5.2. Factors affecting the health status of fish (Jeney, 2017)

Classification of Diseases in Aquaculture

Diseases in aquaculture can be categorized into several groups: non-infectious diseases, viral diseases, bacterial diseases, diseases caused by fungi and fungal-like organisms, and diseases caused by parasites (including protozoa, metazoans, and myxozoans, as well as coccidia, etc.) (Figure 5.3).

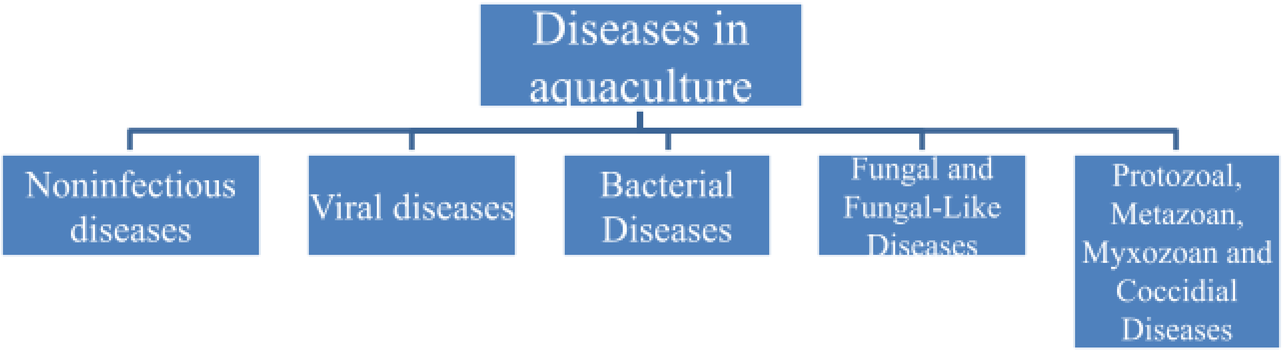


Figure 5.3. Classification of diseases in aquaculture

Detailed information about diseases, aetiology, signalment, risk factors, management, and prevention may be found in specialised sources, books, and databases, for instance:

- Clinical Guide to Fish Medicine. (2021). Wiley eBooks.
- Noga, E. J. (2010). Fish Disease: Diagnosis and Treatment. John Wiley & Sons.

- American Fisheries Society–Fish Health Section. (2014). Blue Book: Suggested Procedures for the Detection and Identification of Certain Finfish and Shellfish Pathogens (2014 ed.). Retrieved from http://afs-fhs.org/bluebook/bluebook-index.php
- The Fish Site. (n.d.). Disease Information. Retrieved from http://www.thefishsite.com/diseaseinfo/
- Minnesota Department of Natural Resources. (n.d.). Fish Diseases. Retrieved from https://www.dnr.state.mn.us/fish_diseases/index.html

Examples of common external or internal lesions indicative of disease conditions in cultured fish are shown in Tables 2 and 3.

Non-infectious Diseases

Non-infectious diseases are related to water quality (low dissolved oxygen, gas supersaturation, barotrauma, temperature stress, pH stress, and toxicity from ammonia, nitrites, nitrates, chlorines, heavy metals, hydrogen sulphides, pesticides, etc.) or other causes (trauma, exertional myopathy, lateral line depigmentation, thyroid hyperplasia, mucometra and ovarian cysts, egg retention or binding, dystocia, cataracts, lipid keratopathy, micronutrient deficiency, gastrointestinal foreign bodies, and neoplasia (Clinical Guide to Fish Medicine, 2021).

1.2. Infectious Diseases by Pathogen Type

Viral Diseases

Most of the commonly known viral pathogens of fish are from three families:

- *Herpesviridae, Rhabdoviridae,* and *Iridoviridae*.

The following fish viral diseases are most dangerous and reportable to the OIE (World Organisation for Animal Health), regional and national organisations, responsible for animal diseases (Clinical Guide to Fish Medicine, 2021):

- Koi herpesvirus.
- Viral haemorrhagic septicaemia.
- Infectious haematopoietic necrosis.
- Spring viraemia of carp.
- Epizootic haematopoietic necrosis.
- Red seabream iridovirus.
- Infectious salmon anaemia.
- Salmonid alphavirus.

Table 5.2. Examples of common external lesions indicative of disease conditions in cultured fish (Jeney, 2017)

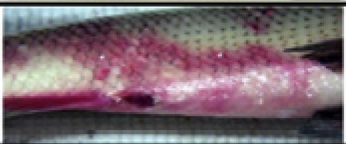
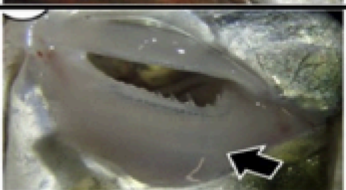
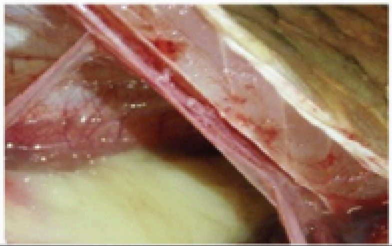
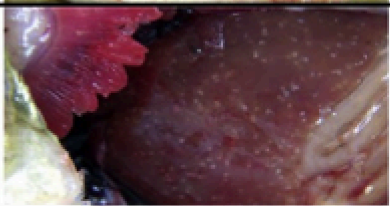
Abnormal Signs	Possible Disease Causes
	Multifocal to coalescing hemorrhage suggestive of a systemic viral and/or bacterial infection, or heavy external parasitism
	Diffuse hemorrhages, along with a hemorrhagic vent, suggestive of a systemic subacute viral and/or bacterial infection
	Furuncle suggestive of infection with *Aeromonas salmonicida*
	Deep hemorrhagic ulcer suggestive of bacterial infection
	Fin erosin and deep ulcer on the caudal peduncle suggestive of flavobacterial infection
	Exophthalmia with an ocular hemorrhage suggestive of a systemic viral and/or bacterial infection
	Severely pale gills suggestive of anemia, possibly induced by viral or bacterial infection
	Gills showing extensive tissue loss suggestive of flavobacterial infection and some viral infections (e.g., Koi herpervirus)

Table 5.3. Examples of common internal lesions indicative of disease conditions in cultured fish (Jeney, 2017)

Abnormal Signs	Possible Disease Causes
	Presence of fluids in the abdominal cavity suggestive of a systemic bacterial and/or viral disease
	Hemorrhage in visceral fat suggestive of nutritional deficiency or systemic viral/bacterial disease
	Multiple whitish nodules in the liver suggestive of granulomatous diseases, such as mycobacteriosis, bacterial kidney disease, or piscirickettsiosis. The same lesions can be caused by encysted metacercariae of larval trematodes
	Hemorrhagic inflammation of the intestine suggestive of toxicosis or enteric redmouth disease caused by *Yersinia ruckeri*
	Hemorrhages in the swimbladder suggestive of systemic viral and/or bacterial disease
	Whitish nodules in the kidney parenchyma suggestive of bacterial kidney disease

Bacterial Diseases

Most bacterial diseases of fish are caused by opportunistic Gram-negative bacilli (rods).

Some significant Gram-positive bacterial infections have also been reported (e.g. *Streptococcus* spp. and *Renibacterium* spp.; *Mycobacterium* spp. may also retain Gram stain).

Morbidity and mortality are often secondary to stressors. Systemic infections are most common, although local infections can also occur. Clinical signs are often nonspecific, and definitive diagnosis requires ancillary testing. Antibiotic treatment should be based on culture and sensitivity testing (Clinical Guide to Fish Medicine, 2021).

Fungal and Fungal-like Diseases

Fish are susceptible to a variety of fungal and fungal-like diseases. Oomycetes, *Exophiala spp.*, *Fusarium spp.*, microsporidians, and mesomycetozoa are the most common fungal pathogens.

Oomycota (Saprolegniasis). Oomycota, commonly known as oomycetes or water molds, are fungal-like organisms that can infect the skin or gills of fish, fish eggs, and any decaying matter.

- They are common opportunistic pathogens of freshwater and brackish fish and are a particular issue for catfish in aquaculture.
- Infection is often secondary to trauma or temperature stressors.
- Typical oomycetes can be treated using medical and husbandry management, although recurrence is common.
- Atypical oomycetes are more invasive and result in severe chronic inflammation.
- Aphanomyces invadans is an atypical oomycete that causes seasonal epizootics in wild and cultured freshwater and brackish fish.

Protozoal, Metazoan, Myxozoan, and Coccidial Diseases

Ichthyophthirius multifiliis is a ciliated protozoan ectoparasite that infects the skin and gills of freshwater bony fish. The disease is often referred to as freshwater ich or white spot.

Metazoans are multicellular eukaryotic organisms. Monogeneans are flatworms (flukes) that are common ectoparasites of fish. Capsalids are large, oval, oviparous monogeneans. They infect the skin, eyes, and gills of marine fish. Leeches are hematophagous metazoan parasites. They are often visible on the skin and fins.

Myxozoans are common parasites of wild-caught fish and pond aquaculture. Most of these parasites have an indirect life cycle, usually involving an oligochaete, polychaete, or bryozoan.

1.3. Major Diseases of Molluscs, Crustaceans

Worldwide, protozoan parasites are the most significant cause of losses to bivalve industries. This predominance of protozoan parasites is reflected in a guide to diseases for the mollusc farmer (Elston, 1990). Of the 11 ‘Notable Oyster Diseases’ described in this guide, seven are caused by protozoans:

- *Perkinsus marina.*
- *Haplosporidium nelson.*
- *Haplosporidium costalis.*
- *Bonamia mackini.*
- *Bonamia Ostrea.*
- *Marteilia refringens.*
- *Hexamita nelson.*

It is not just protozoans that cause disease in molluscs; however, viruses and bacteria are also involved. Viruses have caused hatchery mortalities and considerable grow‐out problems in marine shrimp culture. The most devastating virus known to date is the white spot syndrome virus (WSSV) (Lucas et al., 2019).

1.4. Spread of Pathogens in Aquaculture

The spread of pathogens is a density‐dependent process and is therefore affected by stocking rates. There is a relationship such that the greater the density, the smaller the distance between neighbours. This leads to a higher likelihood of pathogens crossing the distance between hosts in a viable state.

Immobile pathogens, such as viruses, non-motile bacteria, sporozoans, and parasite eggs, follow diffusion laws. Therefore, in still water conditions, a concentration gradient of these pathogens will form around an infected individual.

Other pathogens, such as bacteria, fungal zoospores, protozoa, and metazoans, generally have active but variable dispersal capabilities. As distance increases, fewer pathogens will be able to reach susceptible hosts to establish or continue a disease epidemic (outbreak). As there is natural attrition of pathogens in the environment, if the pathogen does not reach a susceptible host in a defined period, the chance of establishing a new infection is almost zero (Lucas et al., 2019).

By stocking facilities with monocultures, aquaculture excludes both predators and competitors of the species being grown. A large number of the prey items of the cultured species are also excluded. Exclusion of cohabiting animals leads to the removal of both intermediate and definitive hosts from the aquaculture ecosystem. This effectively breaks the life cycle of many of the multi‐host helminths (e.g., digeneans and cestodes), which consequently have less of a role in disease in aquaculture than

in wild populations. Sea cages are much less effective at breaking these life cycles than ponds or recirculation systems (Lucas et al., 2019).

Global warming can alter the distribution and prevalence of pathogens by changing environmental conditions and disrupting ecosystems. New pathogens may emerge, or previously rare pathogens may become more common. Aquaculture species may encounter new or more aggressive pathogens that they are not adapted to handle, increasing the risk of disease outbreaks and complicating management efforts.

Methods of Fish Diseases Treatment

Various methods of treatment and drug application control fish diseases, as described by Parker (2011).

Dip. In the dip method, a strong solution of a chemical is used for a relatively short time. This method can be dangerous because the solutions used are concentrated. The difference between an effective dose and a lethal one is usually very slight. Fish are typically placed in a net and dipped into a strong solution of the chemical for a short period, usually 15 to 45 seconds, depending on the type of chemical, its concentration, and the species of fish being treated.

Flush. This method is relatively simple and involves adding a stock solution of a chemical to the upper end of the unit to be treated, then allowing it to flow through the unit. An adequate water flow must be available so that the chemical can be flushed through the unit or system in a short time. This method cannot be used in ponds.

Prolonged. There are two types of prolonged treatments: a short-term, or bath, treatment and an indefinite, or ongoing, treatment.

Bath. The required amount of chemical or drug is added directly to the rearing or holding unit and left for a specified time, usually one hour. The chemical or drug is then quickly flushed with fresh water. Several precautions must be observed with this treatment to prevent severe losses. Although a treatment time of one hour may be recommended, fish should be observed during the treatment period. At the first sign of distress, fresh water is added quickly. The use of this method requires extreme caution to ensure that the chemical is evenly distributed throughout the unit, thereby preventing the occurrence of a chemical hot spot.

Indefinite. Usually, this method is used for treating ponds or hauling tanks. A low concentration of a chemical is applied and allowed to dissipate naturally. This is generally one of the safest treatment methods. One major drawback is the large amounts of chemicals required, which can be prohibitively expensive. As in the bath treatment, the chemical must be distributed evenly throughout the unit to prevent hot spots.

Feeding. In the treatment of some diseases, the drug or medication must be fed or in some way introduced into the stomach of the sick fish. This can be done by either incorporating the medication into the food or by weighing out the correct amount of drug, placing it in a gelatine capsule, and then using a balling gun to insert it into the fish's stomach. This type of treatment is based on body weight.

Injections. Large and valuable fish, particularly when only small numbers are involved, can sometimes be treated most effectively by injecting the medication into the body cavity, intraperitoneally (IP), or into the muscle tissue, intramuscularly (IM). Most drugs work more rapidly when injected IP than IM. IP injections require caution to prevent damage to internal organs. The easiest location for IP injections is the base of one of the pelvic fins. For IM injections, the best location is usually the area immediately next to the dorsal fin (Parker, 2011).

Changes in environmental conditions can lead to shifts in pathogen populations and the emergence of new or more virulent pathogens, the appearance of previously unrecognised diseases, increased disease outbreaks, and challenges in diagnosis and treatment.

2. Protective Measures and Biotechnological Applications to Mitigate Disease Impacts

Fish health management refers to the practices designed to prevent fish diseases. Once fish get sick, salvage is complex. Successful fish health management begins with disease prevention rather than treatment. Good water quality management, nutrition, and sanitation prevent

fish diseases. Without this foundation, outbreaks of opportunistic diseases are impossible to prevent. The fish is constantly bathed in potential pathogens, including bacteria, fungi, and parasites. Poor water quality, inadequate nutrition, or immune system suppression, often associated with stressful conditions, enable these potential pathogens to cause disease. Medications used to treat diseases buy time for fish and enable them to overcome opportunistic infections, but they are no substitute for proper animal husbandry (Parker, 2011).

Global warming necessitates regular and comprehensive monitoring of water quality, pathogen levels, and health indicators. This monitoring involves utilising advanced diagnostic tools and surveillance techniques to detect and address disease outbreaks promptly.

2.1. The Philosophy of Disease Control

Disease control in aquaculture is usually attempted on the assumption that an absence of pathogens is the desired state. However, the likelihood of initiating an aquaculture venture without any potential pathogens in the system is very slim, and the question arises as to whether it is cost-effective to achieve a pathogen-free state. This 'total elimination of pathogens' strategy is the classic approach to disease control: the pathogenocentric approach (Lucas et al., 2019).

There are several factors to consider when deciding on control measures in aquaculture:

- **The cost of the control measure**. Some pathogens make culture uneconomical in their presence, and they must be removed from the culture system.
- **The likelihood of reinfection**. Ideally, there should be almost no chance of the pathogen being re-acquired from the environment or wild stocks in the vicinity. Alternatively, infection with a pathogen and subsequent treatment often allow the vertebrate immune system to be primed, thereby limiting further infections.
- **An adequate assay for the pathogen**. It must be possible to accurately identify the pathogen in order to assess the effect of the control measures on it.

Generalised Disease Management Techniques

The most significant factor in the movement and introduction of pathogens to farms, and indeed on any geographical scale, is the movement of animals. This includes:

- live broodstock in particular;
- live larval forms for stocking;
- live alternative hosts;
- frozen carcasses for human consumption;
- aquaculture feeds; and
- bait.

The majority of new introductions of pathogens to uninfected systems are due to the unrestrained movement of contaminated animals. Sometimes this is unavoidable, as aquaculture does not exist without either broodstock or live juveniles for stocking. However, the biosecurity of broodstock, the number one contaminant, has often been neglected and should be the first point considered. Thus, in Europe, it is mandatory to have broodstock tested for a broad range of notifiable diseases (bacterial and viral) before transfer is permitted (Lucas et al., 2019).

If pathogen‐free broodstock are not available, what is the pathogen status of the broodstock that is being used? For example, in marine finfish aquaculture and shrimp aquaculture, viral encephalopathy and retinopathy and white spot syndrome virus, respectively, are all spread vertically from broodstock to larvae and then distributed through infected postlarvae and juveniles to farms.

Whilst it is impossible to have strategies that will work for all pathogens, several procedures can help limit pathogens within culture systems (Lucas et al., 2019).

- **Batch Culture**. Batch culture works on the 'all in, all out' principle.
- **Incoming Water Treatment**. Treatment of incoming water is essential in recirculating culture systems. It is more useful in hatcheries than in grow-out situations due to the sheer volume of water involved in the latter. Water treatment includes chemical sterilisation (chlorine, iodophores, ozone) and physical sterilisation (UV light).
- **Lower Stocking Density**. By lowering the stocking density, the average 'inter‐fish' distance is increased and the probability of a pathogen reaching the next host is reduced on an exponential scale. Theoretically, disease epidemics will decline to extinction unless a threshold number of hosts is present in a given area. Simplistically, each infected host must infect at least two other hosts as it succumbs, or the epidemic will not propagate. Furthermore, lowering stocking densities will also decrease the level of sibling interaction‐induced stress and competition for space and food.
- **Single Spawning Stockings**. Differential growth is a reliable indicator of poor health in captive populations. Runts are very useful for screening diseases, as they are either stunted by pathogens or behaviourally and nutritionally stressed due to being at the bottom of a pecking order. Such stressed animals will also express pathogens. If a mixed spawning population is used to stock a culture system, the differential growth due to age, genetics, or variations in hatching conditions will obscure pathogen‐caused differential growth. Thus, stocking with a single spawning is particularly beneficial for an aquatic pathobiologist. This

technique is not as valuable for many finfish species, where size grading is a regular part of culture (e.g., eels, salmon, and trout); however, it works well for invertebrates (e.g., freshwater crayfish). This technique also highlights a prevalent problem among fish farmers. At harvest, most fish farmers will place the runts, which are too small to meet market needs, in a pond to allow them to grow to market size. This overlooks the most likely reasons for their failure to reach market size: they are compromised by having a disease. Therefore, in reality, the farmer is keeping a reservoir of diseased individuals on the farm to infect the next batch of stock.

- **Specific Pathogen‑Free Broodstock**. Most pathogens are more virulent in the younger stages of a host. By producing offspring from broodstock free of specific pathogens, the offspring have a good chance of growing to a non‑susceptible size before being infected. Thus, a crop can be produced even in an area where disease regularly affects animals. This approach can also be practical if all life stages are equally susceptible; however, by late infection of the host, the crop can be harvested before the disease has a chance to establish.
- **Stress Reduction**. Stress is often used as an excuse for problems when no other logical explanation is available. Despite the nebulous use of the concept of stress, it has a factual physiological basis and consequences. Unfavourable conditions lead to an adaptive response, and a new level of homeostasis is achieved. If this is not achieved, then exhaustion follows along with the overproduction of stress hormones. The two most practical ways to limit stress are to increase aeration, thereby alleviating any oxygen stress that may occur, particularly during hot summers, and to lower stocking density.
- **Vaccination**. Vaccination works on the premise that an immunological memory exists, allowing for a stronger and quicker immune response following prior exposure to a pathogen (Lucas et al., 2019).

2.2. Biotechnologies in Disease Management

Fish Vaccination

The term vaccine is now used more generally to define any preparation used to confer immunity to a disease by inoculation, and the principle relies on the recipient having an adaptive immune system, which initiates a response to the components of the vaccine that results in the memory of those components. The immune system of the vaccinated individual is then able to respond more quickly and activate protective effector systems with greater magnitude on subsequent encounters with the same patterns or structures (Fig. 5.4) (Lucas et al., 2019).

Immunisation of aquaculture fish has been started for over 50 years. Vaccination is an effective means to prevent bacterial and viral diseases. Vaccination also contributes to the environmental, social, and economic sustainability of the aquaculture industry. Unfortunately, vaccine development in the aquaculture industry lags significantly behind that of the livestock industry. Only a few vaccines have been registered and approved in the industry. Furthermore, vaccination in fish is a labour-intensive process, where individual fish are manually injected with a dose of a vaccine. Oral vaccines are an alternative to labour-intensive traditional vaccination with hand injection. Oral vaccination minimises handling and damage to fish, thus reducing mortality rates during the vaccination. Microencapsulation, in which antigens from pathogens are incorporated, may be a technology for delivering oral vaccines to fish. There are ways to develop groundbreaking vaccines for oral delivery systems. However, it seems that there is currently no effective oral vaccine available in the aquaculture industry (Yue & Shen, 2021).

Due to global warming, it is necessary to develop and administer vaccines to protect aquaculture species from specific diseases that threaten their survival. Ongoing research into new vaccines and immunisation strategies is essential. The development and implementation of effective vaccination programs to prevent outbreaks of diseases caused by climate change are required.

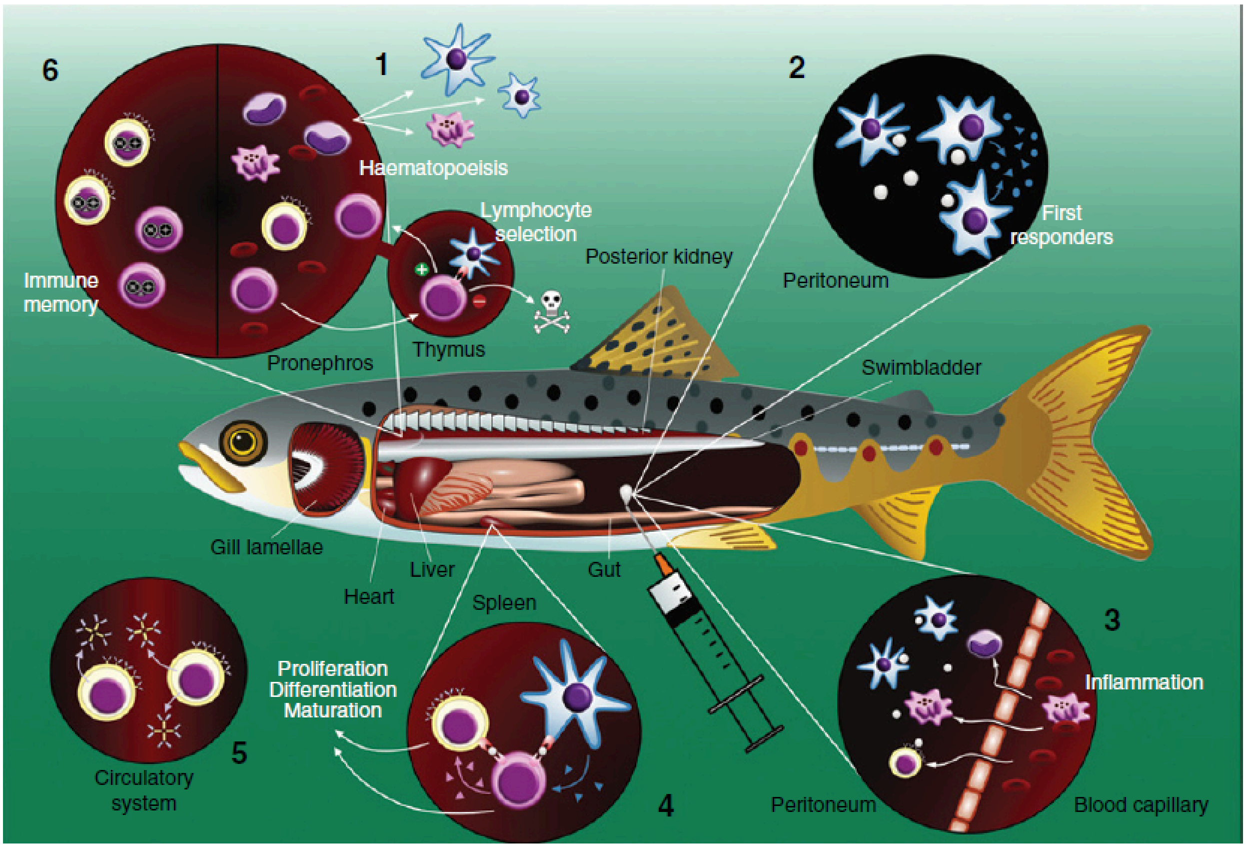


Figure 5.4. Schematic representation of Atlantic salmon parr showing the primary immune tissues and the progression of the response to vaccination by intraperitoneal injection (Lucas et al., 2019).

Immunomodulators and Immunostimulants

Substances that induce, enhance, or suppress the immune response are collectively referred to as immunomodulators, and these have the potential to reduce disease-related losses in aquaculture significantly. There is a diverse range of substances (recombinant, synthetic, and natural) that offer an attractive alternative to antibiotics as they generally have fewer side effects than existing medicines, and it is less likely that the pathogen will develop resistance against them (Jeney, 2017).

Immunostimulants are substances that stimulate the immune response of fish by inducing or increasing the fish's immune activity, either through antigen-specific responses, such as vaccines, or non-specifically, independent of antigenic recognition, such as adjuvants or nonspecific immunostimulants. Adjuvants are added to vaccines to enhance the generation of a stronger protective response to the antigens present in the vaccine and to provide increased protection against the pathogen. Cytokines produced by the cellular immune system also function as immunostimulants, enhancing immune function.

Immunostimulants are derived from both natural and synthetic sources. Examples of immunostimulants include β-glucans, chitin, lactoferrin, levamisole, vitamins B and C, growth hormone, and prolactin. Immunostimulants have been shown to improve fish's resistance to disease and enhance their immune response at times of stress. Their use is now commonplace in disease control programs to help prevent infectious diseases in aquaculture, especially since they can be easily

fed to fish. β-glucans are the most commonly used immunostimulants in aquaculture, particularly β-glucans (β-1,3 and 1,6-glucans) derived from the cell wall of the baker's yeast *Saccharomyces cerevisiae*. However, other sources of β-glucan have been investigated (Jeney, 2017).

Probiotics, Prebiotics, and Adaptive Feeding

Probiotics are live microorganisms, derived from 'normal' environmental or intestinal bacteria that have the potential to provide health benefits when administered to fish. They are defined as 'beneficial live micro-organisms when administered to a host at an effective dose'. Selected bacteria within the species *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Enterococcus*, *Carnobacterium*, *Shewanella*, *Bacillus*, *Aeromonas*, *Vibrio*, *Enterobacter*, *Pseudomonas*, *Clostridium*, *Saccharomyces*, *Pediococcus*, and *Streptococcus* have been investigated as potential probiotics for aquaculture. The action of probiotics is based on their ability to stimulate the growth of specific microbes in the fish's intestinal tract. They maintain the microbial equilibrium of the gut by competing with pathogenic bacteria for attachment sites on the gut mucosa and also by competing for nutrients. They have an antagonistic activity against the pathogen, as they produce a variety of antimicrobial substances (bactericidal or bacteriostatic) that prevent the replication and/or kill the pathogen, thus preventing the pathogen from colonising the fish's gut. They also directly enhance the host's immune system response against the pathogen (Jeney, 2017).

Prebiotics are indigestible carbohydrates that confer health benefits when fed to the host by stimulating the growth and/or activity of selected bacteria in an animal's gut. Fermentable carbohydrates are considered the most promising of these, exerting a positive effect on the composition and activity of indigenous microflora in the gut tract. Several potential prebiotic carbohydrates have been tested in aquaculture. The prebiotics are metabolised in the gut of the host by bacteria such as *Lactobacillus* and *Bifidobacterium*, and these, in turn, produce metabolites such as short-chain fatty acids, which are important for colon health. They also decrease the level of intestinal pathogens present in the gut (Jeney, 2017).

Use of probiotics and immunostimulants in feed to boost the immune system of aquaculture species, enhancing their resistance to diseases, is one of the important factors for minimising the effects of climate change.

Considering the impacts of environmental changes on growth and health, it is necessary to modify feed formulations and feeding practices. This requires adjusting nutrient profiles based on water temperature and quality and providing specialised feeds to support immune function and stress resilience. At the same time, it requires monitoring of feed efficiency and making adjustments as needed. What should change in feed and feeding in aquaculture due to global warming is described in a separate chapter.

2.3. Integrated Pathogen Management Strategies in Fish Farming

The impact of pathogens on aquaculture is substantial – the financial losses are estimated to be roughly 20% of the total production value. The main goal of Integrated Pathogen Management (IPM) is to combine all the available preventive and curative methods to minimise the impact of pathogens in the production chain, and at the same time minimise the impact on the environment and avoid future side effects, therefore increasing sustainability, at both economic and environmental levels (Jeney, 2017).

The term IPM comprises the following:

Integrated. It is a holistic approach, as it combines all available strategies to control disease, with a focus on the interactions between pathogen, host, and environment. The relationship between these three factors is complex, as the mere presence of a pathogen does not necessarily lead to the development of disease. This interaction, while complicating the epizootiology of diseases, provides opportunities to minimise the impact of the infection.

Pathogen. This means any organism that conflicts with plant or animal production. If an organism does not have a profound impact, it is not worth developing IPM for it. IPM works particularly well for pathogens with complex life cycles, providing multiple opportunities for intervention.

Management. It is a way to keep pathogens below the levels at which they can cause severe economic damage. It does not always mean eradicating the pathogens. It means finding strategies that are effective, economical, and minimise environmental damage.

The development of IPMS is a process consisting of several steps, summarised in Figure 5.5 (Jeney, 2017). The process is initiated when a pathogen causes a disease outbreak. The **first step** involves gathering all the possible **knowledge** on the key pathogen(s) (life cycle, host-invasion strategies, natural enemies, vectors, etc.), as well as host and environmental risk factors that favour pathogen spread and impact within a fish population. This information originates primarily from farmers' experiences, scientific studies, and literature reviews. The **second step is prevention**, which involves the development, evaluation of feasibility and cost-benefit, and implementation of the best preventive strategies for each pathogen. The **third step** involves monitoring the disease, which includes detecting the pathogen, surveilling the host's performance, and assessing the potential environmental impact. When prevention is insufficient to stop the disease, **the fourth step** is intervention, which involves developing, evaluating the feasibility and cost-benefit, and implementing physical, chemical, and/or biological treatments. Monitoring also occurs after intervention. **The fifth step** involves reevaluation and planning based on the results from various strategies. IPMS must be constantly assessed and refined to maximise their benefits. This involves revising disease records, reevaluating costs/benefits, consulting and adapting to innovations, and engaging in continuous learning. Ideally, it should enable one to define prediction models in the long term. Step 5 feeds back to step 1, increasing the body of knowledge. In this chapter, we will describe the available choices for most of these steps in fish farming, which are the current limiting factors for their implementation in the production sites, and the future perspectives (Jeney, 2017).

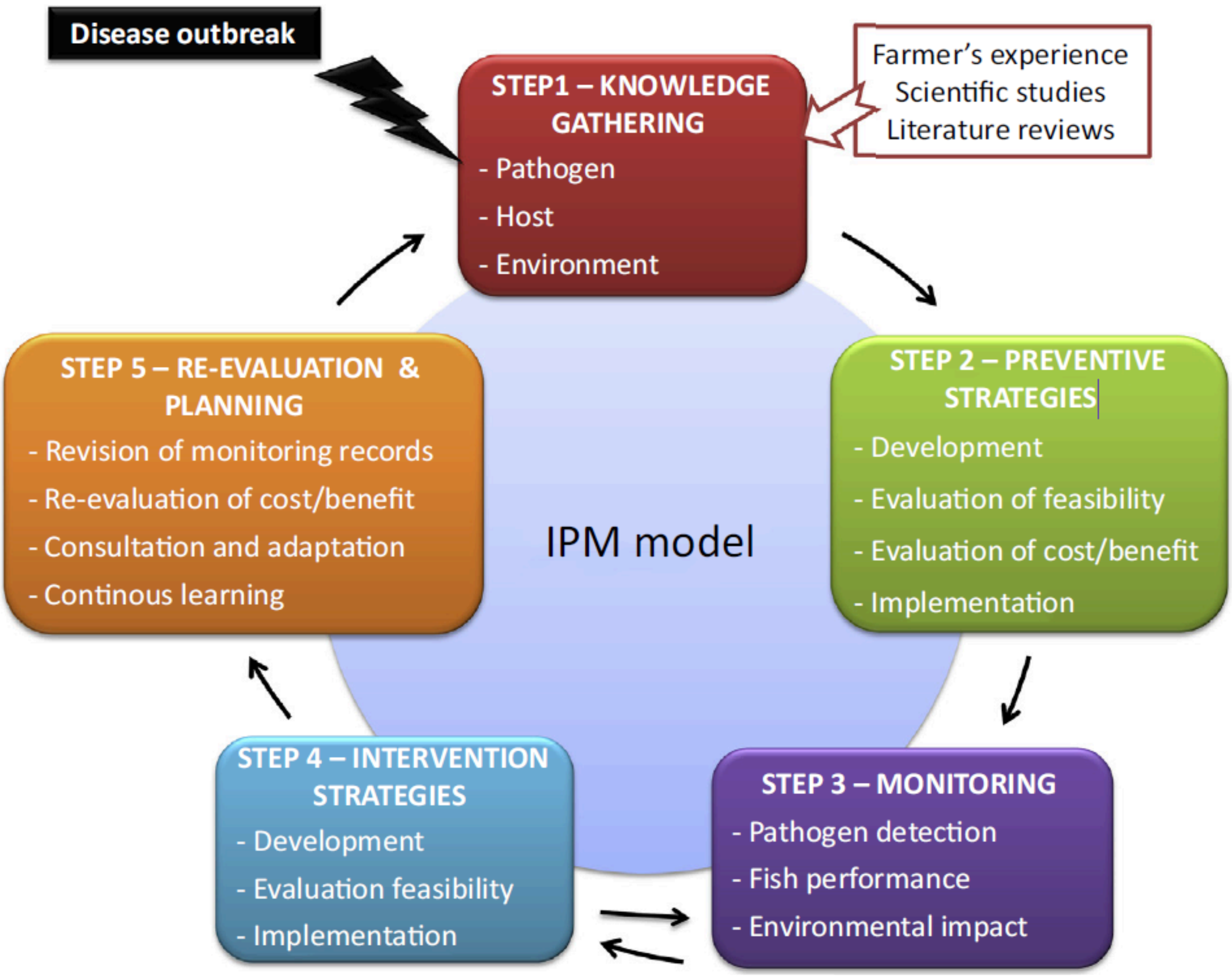


Figure 5.5. Development process of integrated pathogen management (IPM) strategies for fish diseases (Jeney, 2017)

Global warming has a significant impact on the incidence and management of diseases in aquaculture systems. By understanding the interplay between environmental changes and disease dynamics, aquaculture operations can implement effective management strategies to mitigate these impacts. Enhanced monitoring, temperature and water quality control, health management practices, and infrastructure resilience are key to maintaining the health and productivity of aquaculture species in a changing climate.

Basic Requirements for Biosecurity in Aquaculture Farm

Basic requirements (typical in Lithuania) for biosecurity in an aquaculture farm are:

1. Every aquaculture enterprise must have a biosecurity plan in place to prevent contamination from entering the farm and/or spreading the infection outside the farm.
2. The wheels of each entering vehicle or other transport must be disinfected.
3. Monitor water quality parameters in fish reservoirs and ponds.
4. Disinfection mats or tubs must be placed at each entrance/exit from the premises, both inside and outside the building.
5. Employees must change into work clothes when they come to work and change again when they leave.
6. Employees working in departments of different growth stages of fish must disinfect their hands every time they move from one room to another.
7. Tools for fish catching, transporting, feeding, and cleaning cannot be used in several rooms.
8. Used tools and equipment must be stored in a saline solution until subsequent use.
9. Limit the number of visitors, and upon their arrival, register them and use disposable clothing for protection.
10. Workers can only work on one aquaculture farm to avoid transmission.

A fish-health management plan at the facility level is invaluable, but indeed may not be adequate for preventing the spread of pathogens to or from wider geographic locations. Therefore, policies and regulations at the regional/national and international levels must be implemented (Jeney, 2017).

Other Protective Measures for Minimising Climate Change Impact and Disease

Very important for aquaculture infrastructure is to select sites that reduce the risk of disease transfer and minimise the climate change impact.

Depending on the type of culture system and the species cultured, proper site selection can significantly reduce the risk of disease transfer. Appropriate sites provide environmental conditions (such as water temperature and salinity) that minimise physiological stress, thereby reducing the incidence and severity of infectious diseases within the facility. The quality of the available water should also be taken into consideration. The volume of water and its varying availability over time may limit production capacity. Facilities with insufficient water supplies are often plagued by poor fish performance, more disease problems, and reduced profitability. For earthen pond facilities, it is crucial to ensure that soils are not contaminated with compounds that could enter the water column and adversely affect fish health or otherwise contaminate fish flesh (Tucker & Hargreaves, 2009).

Extreme weather can cause physical damage to aquaculture infrastructure, lead to sudden changes in water quality, and introduce pathogens and pollutants into aquaculture systems. This can result in disease outbreaks and operational disruptions.

Global warming and its outcomes can cause physical damage to tanks or cages, deteriorate water quality, and increase disease incidence due to contamination or stress. Additionally, operational challenges may arise in the management and maintenance of aquaculture systems.

Appropriate sites also reduce the likelihood that natural phenomena (such as floods, storm surges, or large waves) will cause facility biosecurity breaches, allowing pathogen release or the escape of infected fish. Site selection should also consider whether sensitive populations of wild fish are placed at risk. Sensitive populations may include threatened or endangered species, as well as migrating populations of susceptible species (Tucker & Hargreaves, 2009).

Due to global warming, it may be necessary to strengthen existing structures, elevate facilities to prevent flood damage, and incorporate flexible and resilient systems. Additionally, developing and maintaining emergency response plans to address infrastructure damage, water quality issues, and disease outbreaks caused by extreme weather.

Species of aquaculture with greater thermal tolerance, which can better withstand higher temperatures and reduce disease susceptibility, may be selected.

More measures and innovative solutions can be implemented in RAS. Maintaining optimal temperature ranges can help manage stress and reduce disease risks, as preventive measures can be implemented through temperature control technologies that allow for real-time data-driven adjustments. Regular testing and optimisation of water quality parameters, such as pH, dissolved oxygen, and nutrient levels, can be automated. Techniques such as shading, aeration, and controlled feeding can be implemented to mitigate the effects of temperature and other environmental stressors on aquaculture systems.

System selection and measures against global warming in aquaculture are described in a separate chapter.

3. Climate Impacts on Diseases and Future Solutions

3.1. Influence of Climate Factors

Intensification. Even under consistent environmental conditions, it poses sustainability risks and challenges that require stringent management to respond effectively to pathogen detection and/or disease outbreaks. Climate change will exacerbate those threats and challenges.

Large-scale production of a single species within a production environment needs:

1) a rapid response to off-feed animals, signs of morbidity, and mortalities;

2) capacity to isolate affected animals from unaffected populations and farms; and

3) capacity to depopulate affected sites where treatment is not feasible.

Increasingly, intense farming is being impacted by weather extremes that stress farmed animals and impede management mechanisms, e.g., prevention of escapes (destruction of holding systems) and isolation of diseased and stressed animals from unaffected animals (Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, 2018).

Species and Genetic Diversification. Over the last 30 to 40 years, aquaculture has evolved through the use of species diversification (selecting species that yield the best production results under farmed conditions) and the development of genetic strains under experimental conditions for commercial production.

Both selection methodologies include disease tolerance (infection without significant mortality) and resistance (the ability to prevent infection). Species and strain selection advantages, however, rely on consistent environmental parameters in a production system, i.e., no significant changes to production conditions. Where such conditions are subject to 'extremes' (temperature, salinity, turbidity) selected species and/or strains may be more vulnerable to high losses than less-selected and more genetically diverse stocks; primarily that native to the production area (Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, 2018).

Expansion Outside the Natural Species' Geographic Range. Native species used in aquaculture that exhibit robust farmed production are often subject to farm expansion to the peripheries or beyond their natural geographic range. The animals may be able to withstand slight seasonal temperature and/or salinity changes, but are at a survival disadvantage when extreme conditions impact normal reproductive or growth production cycles.

As for intensification and species and genetic diversification, where such environmental changes occur, resistance to opportunistic or primary pathogen infections can be significantly reduced (Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation, and mitigation options, 2018).

3.2. Genetic Engineering, Marker-assisted Selection, and CRISPR

Biotechnologies, including sex control, polyploidisation, gynogenesis, and androgenesis (Figure 5.6), have played a crucial role in enhancing aquaculture productivity (Yue & Shen, 2021).

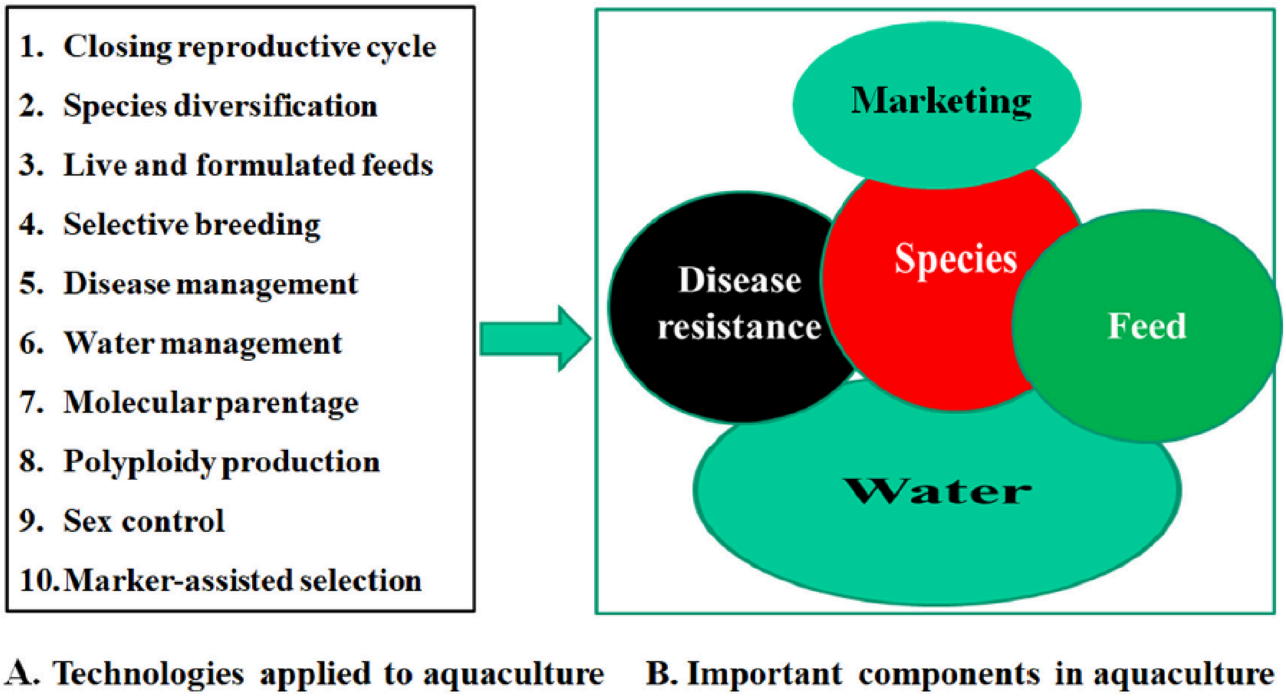


Figure 5.6. Technologies applied in aquaculture leading to the rapid increase of aquaculture production (Yue & Shen, 2021)

Genetic improvement through breeding has been a key factor in the growth of world aquaculture.

The combination of molecular technologies with existing breeding programs has significantly accelerated the genetic improvement of some aquaculture species. Marker-assisted selection (MAS) has already been applied to improve disease resistance (for instance, resistance to IPN in salmon) (Yue & Shen, 2021).

Genomic selection (GS) is a novel approach to molecular breeding. GS uses many markers as predictors of performance and consequently delivers more accurate predictions of breeding values. With the continuous advances in sequencing and bioinformatic technologies, and the decrease in cost of SNP (single-nucleotide polymorphism) genotyping, GS using SNPs covering the whole genome and/or using selected SNPs associated with traits is increasingly being applied across the broad range of aquaculture species to optimise selective breeding and accelerate genetic improvement (Yue & Shen, 2021).

Genome editing (GE) using CRISPR–Cas can accelerate the genetic improvement of aquaculture species when the target genes are known. GE allows for the rapid introduction of favourable alleles into the genome, increasing the frequency of desired alleles at loci determining important traits, generating new alleles, and/or introducing favourable alleles from other species. Aquaculture species are especially suitable for GE due to their high fecundity and external fertilisation, which enables genome editing for many individuals simultaneously.

Advances in GS and GE are poised to dramatically reshape the aquaculture industry by helping improve the economically important traits of many aquaculture species. In the future, combining GS and GE with advanced conventional breeding strategies and matured biotechnologies will substantially accelerate genetic improvement in aquaculture (Yue & Shen, 2021).

Global warming and breeding, as well as biotechnology in aquaculture, are described in a separate chapter.

3.3. Responding to the Challenges of the Future

New approaches have reduced disease incidence and reliance on antibiotics and chemical therapeutics. In Norway, the development of vaccines and improved biosecurity (control and containment of diseases) has dramatically reduced the need for antibiotics in salmon production. Required investments in biosecurity to minimise the risk of disease outbreaks will vary by place and scale. However, the need for improved diagnostic and surveillance capacity of national veterinary services is one common element. Although aquaculture will continue to face new challenges from diseases, new health management technologies will be developed to address these challenges. The cost of genome sequencing is falling exponentially. This will enable the development of diagnostic testing methods, drugs, and other therapies tailored to specific pathogen strains, in the form of customised disease treatment (Lucas et al., 2019).

A key megatrend is the acceleration of technological change, especially biotechnology, nanotechnology, and information and computer technology. Research and development of science and technology around the world is accelerating, driven by economic growth and public investment. Sensors, software, and wireless connectivity enable the collection and analysis of data in real-time. Linked to output devices, these allow timely responses to data inputs. For example, video monitoring of salmon feeding enables efficient feeding, resulting in better feed conversion, reduced waste, and lower pollution. Oxygen sensors in ponds, linked to analysis and control software, can activate aerators to regulate the pond's oxygen concentration. The 'Internet of Things' will be supported by the development

of sensors, automation, autonomous machines, drones, and submersibles. Digital and robotic technologies will increasingly augment or replace workers (Lucas et al., 2019).

Technology plays a central role in enhancing the productivity and environmental sustainability of aquaculture. Key areas for innovation include feeds, genetic improvement, disease control, seed production, and grow-out production systems (Lucas et al., 2019).

Investing in research to understand the effects of global warming on disease dynamics and develop innovative solutions for disease prevention and management is essential.

Intensive collaboration with researchers and institutions to explore new technologies, disease-resistant strains, and adaptive management practices should be a way to minimise the impacts of global warming and effective disease management practices.

Aquaculture requires an increasing number of educated practitioners and experts. Training workshops, webinars, and resources on disease prevention, environmental management, and adaptive strategies are beneficial and essential.

Summary

Global warming impacts the health and management of aquaculture species through various mechanisms, including increased disease prevalence, compromised immune function, and degraded water quality. Effective management requires a multifaceted approach that includes enhanced monitoring, environmental control, water quality management, health management, infrastructure resilience, and adaptive feed practices. By implementing these strategies and staying informed about emerging challenges and solutions, aquaculture operations can better protect their species and ensure sustainable production in the face of a changing climate.

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Chapter 6. Selection of Systems for Aquaculture under Global Warming

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Introduction

Global warming has a significant impact on aquatic ecosystems and aquaculture, necessitating the adoption of resilient systems to address challenges such as rising temperatures, oxygen depletion, and increased disease prevalence. Sustainable aquaculture practices are critical in mitigating these impacts, with system selection playing a key role in ensuring adaptability and long-term viability. This chapter provides a comprehensive examination of the effects of climate change on aquaculture systems, exploring innovative solutions and strategies to guide policymakers, researchers, and industry stakeholders in fostering sustainability in the sector. Research highlights the importance of incorporating climate-resilient technologies, such as recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA), to enhance productivity and reduce environmental footprints (Boyd et al., 2022; Handisyde et al., 2017; Froehlich et al., 2018).

Aquaculture is one of the fastest-growing food production sectors globally and plays a critical role in meeting the nutritional needs of a growing human population. However, the impacts of global warming have introduced significant challenges to its sustainability. Rising global temperatures, ocean acidification, shifts in salinity, and the proliferation of pathogens are reshaping aquatic ecosystems, presenting new challenges for aquaculture operations. These environmental changes threaten not only the economic viability of the aquaculture industry but also global food security and biodiversity.

Climate change exacerbates thermal stress in aquatic environments, affecting the metabolic rates, growth, and reproduction of farmed species. According to Boyd and McNevin (2015), temperature fluctuations outside the optimal range for aquaculture species can lead to increased oxygen demand, reduced immune responses, and higher mortality rates. In addition, warming waters are creating favourable conditions for harmful algal blooms (HABs), which can deplete oxygen levels and release toxins harmful to aquatic life (Diaz & Rosenberg, 2008). These phenomena necessitate innovative approaches to the design and management of aquaculture systems.

Ocean acidification, a direct consequence of increased atmospheric carbon dioxide (CO_2) levels, poses another critical challenge. Acidified waters reduce the availability of carbonate ions, which are necessary for shellfish and other calcifying organisms to build their shells and skeletons. Studies by Cooley et al. (2009) highlight the economic and ecological risks associated with acidification, particularly for shellfish industries. Additionally, shifts in salinity caused by melting ice caps and altered precipitation patterns are disrupting the geographical distribution of aquaculture species, necessitating adjustments in operations to accommodate these dynamic conditions (Troell et al., 2003).

Disease proliferation is an escalating concern in aquaculture systems under climate change. Warmer temperatures accelerate the life cycles of many pathogens and parasites, increasing the frequency and severity of outbreaks. For example, *Vibrio* spp., a common pathogen in aquaculture, thrives in elevated temperatures, leading to significant economic losses (Bondad-Reantaso et al., 2005). These challenges underscore the importance of adopting climate-resilient aquaculture systems that can mitigate the adverse effects of global warming.

System selection is a crucial step in adapting to these challenges. Closed Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and offshore aquaculture systems represent innovative approaches that can enhance resilience and sustainability. According to Martins et al. (2010), RAS provides precise environmental control, reducing external stressors on aquatic species. IMTA integrates species with complementary ecological roles, improving nutrient cycling and ecosystem health. Offshore aquaculture, operating in deeper waters with stable environmental conditions, presents a viable alternative to coastal systems that are vulnerable to climate-induced eutrophication and hypoxia (Holmer, 2010; Pereira et al., 2024).

1. Climate Challenges for Aquaculture Systems

Global warming has introduced significant challenges to aquaculture systems, including rising water temperatures, ocean acidification, and altered salinity levels, which compromise the health and productivity of aquatic organisms. Increased thermal stress accelerates metabolic rates, while eutrophication and hypoxia threaten aquatic habitats. Furthermore, climate change enhances the proliferation of diseases and pathogens, particularly in species with narrow environmental tolerances (Boyd & McNevin, 2015; Diaz & Rosenberg, 2008). Understanding these impacts is critical to developing adaptive strategies that ensure aquaculture resilience.

1.1. Thermal Stress

Global temperature increases pose a significant challenge to aquaculture systems, particularly for species with narrow thermal tolerances. For example, studies indicate that rising water temperatures lead to higher metabolic rates in fish, increasing oxygen demand and stress (Boyd & McNevin, 2015).

Rising global temperatures pose significant challenges to aquaculture operations, particularly for species with narrow thermal tolerances. Fish, shellfish, and other aquatic organisms often have a limited range of optimal temperatures necessary for their physiological functions. Elevated temperatures increase metabolic rates, leading to a heightened oxygen demand and physiological stress (Boyd & McNevin, 2015). With rising water temperatures, oxygen availability decreases due to reduced solubility, creating conditions of temperature-induced hypoxia. This phenomenon exacerbates mortality rates in species such as salmon and tilapia, particularly in stratified water bodies where oxygen levels already fluctuate.

1.2. Eutrophication and Disease Proliferation

Climate-induced eutrophication accelerates nutrient loading in aquatic ecosystems by increasing nutrient runoff from agricultural activities and intensifying rainfall events. Excess nutrients, particularly nitrogen and phosphorus, lead to harmful algal blooms (HABs), which release toxins and deplete dissolved oxygen during their decomposition. Eutrophication is a leading cause of hypoxic zones, often referred to as 'dead zones', which render aquatic habitats uninhabitable. For instance, the Gulf of Mexico's hypoxic zone, fuelled by nutrient inputs from the Mississippi River, has expanded due to both anthropogenic and climatic drivers, affecting fish stocks and aquaculture operations.

Warmer waters create conditions favourable for pathogens and parasites, increasing risks in aquaculture systems. For instance, *Vibrio* spp. thrives in elevated temperatures, causing economic losses in shrimp and fish farming (Bondad-Reantaso et al., 2005; Pounds et al., 2006). Furthermore, warmer temperatures weaken the immune systems of aquatic organisms, making them more susceptible to infections. Sea lice infestations in salmon farms, for example, have worsened in recent years, resulting in significant economic losses and an increased reliance on chemical treatments, which carry environmental risks (Abolofia et al., 2017).

1.3. Ocean Acidification and Shifts in Salinity

Ocean acidification is another critical issue impacting aquaculture, particularly shellfish farming. As atmospheric CO_2 dissolves into the oceans, it forms carbonic acid, which lowers pH levels and reduces the availability of carbonate ions essential for shell and skeleton formation in calcifying organisms (Cooley et al., 2009). Molluscs, such as oysters and clams, are particularly vulnerable, with acidified waters leading to thinner shells and lower survival rates. Additionally, acidification disrupts sensory functions in some fish species, altering their predator avoidance behaviours and ecosystem dynamics (Munday et al., 2009).

Melting ice caps and changing precipitation patterns are altering salinity levels in marine and estuarine environments, which in turn affect the distribution and productivity of aquaculture species. Species such as shrimp and sea bass, which are sensitive to fluctuations in salinity, may experience reduced growth and reproduction (Troell et al., 2003). In Bangladesh, rising salinity levels in coastal waters have compelled shrimp farms to adapt by introducing salt-tolerant species; however, these changes come with significant economic and ecological costs.

2. Key Criteria for System Selection

Selecting aquaculture systems that can withstand the adverse effects of climate change is vital for sustainability and economic viability. Key criteria include resilience to temperature fluctuations, mitigation of eutrophication, pathogen control, energy efficiency, and adaptability to changes in salinity. Systems such as Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA) effectively address these challenges by providing environmental control and nutrient cycling, respectively (Martins et al., 2010; Pereira et al., 2024). These criteria ensure the adaptability of aquaculture systems to evolving climatic conditions.

2.1. Resilience to Environmental Changes

Closed Recirculating Aquaculture Systems (RAS) offer precise temperature control, enhancing system adaptability to thermal stress. Systems must be adaptable to temperature variations to reduce thermal stress on aquatic organisms. Closed Recirculating Aquaculture Systems (RAS) are particularly effective, offering precise control of water temperature and other environmental parameters. RAS provides significant advantages in maintaining optimal conditions for species growth and survival (Martins et al., 2010). An example is salmon aquaculture in Norway that utilises RAS technology to mitigate the impacts of rising sea temperatures (Badiola et al., 2012).

Mitigation of Eutrophication

Integrated Multi-Trophic Aquaculture (IMTA) incorporates filter feeders and seaweed to reduce nutrient loading, absorbing excess nutrients, improving overall water quality, and mitigating eutrophication (Pereira et al., 2024). Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable solution for nutrient management. IMTA integrates species such as fish, seaweed, and shellfish to recycle nutrients and reduce eutrophication risks. Seaweed farms in Asia have demonstrated practical nutrient cycling, reducing HABs and improving water quality (Troell et al., 2003).

Pathogen Control

Climate change has exacerbated the risks of pathogens and diseases in aquaculture, as warmer water temperatures accelerate the life cycles of harmful organisms, including bacteria, viruses, and parasites. Advanced pathogen control strategies are essential for safeguarding aquaculture operations against these risks. Biosecure systems, such as Recirculating Aquaculture Systems (RAS), play a critical role by isolating farmed species from external environments, significantly reducing exposure to pathogens. Technologies like ultraviolet (UV) sterilisation, ozone treatment, and biofilters effectively minimise microbial loads in water systems, thereby protecting aquatic species (Bondad-Reantaso et al., 2005). For example, shrimp farms in Southeast Asia have successfully used RAS combined with UV sterilisation to combat *Vibrio* outbreaks, which are often triggered by rising sea temperatures (Aly & Fathi, 2024). Pathogen-resistant aquaculture practices, such as selective breeding for disease tolerance, further enhance resilience in vulnerable species.

2.2. Energy Efficiency and Carbon Footprint

Energy-efficient systems play a crucial role in reducing the carbon footprint of aquaculture operations. The integration of renewable energy sources, such as solar and wind power, and the adoption of efficient technologies, such as advanced aeration systems, are vital for sustainable development in the sector. Recirculating Aquaculture Systems (RAS), while energy-intensive due to water pumping, aeration, and temperature regulation, present a viable pathway to sustainability when powered by renewable energy sources. For instance, hybrid solar-powered RAS setups have been shown to reduce operational energy costs by 30% while maintaining productivity (Manolache & Andrei, 2024).

Innovative energy solutions, such as waste-to-energy systems that convert organic aquaculture waste into biogas, further enhance sustainability by addressing waste management challenges (Martins et al., 2010). Solar-powered aquaculture systems in resource-constrained regions, including sub-Saharan Africa, demonstrate how energy-efficient solutions can foster both environmental and economic sustainability. By leveraging renewable energy and efficient aeration technologies, the aquaculture industry can significantly reduce its environmental impact while promoting long-term resilience and productivity (Badiola et al., 2012).

Adaptability to Salinity Fluctuations

Systems located in coastal and estuarine regions must account for changes in salinity driven by global warming. Euryhaline species, capable of tolerating a wide range of salinities, can be prioritised. Selective breeding programs are often utilised to develop species with enhanced salinity tolerance (Rahman et al., 2021). An example is the adaptation of aquaculture operations in Bangladesh to salinity intrusions by cultivating salt-tolerant species, such as tilapia.

Adaptability to salinity fluctuations is a crucial factor for aquaculture systems, particularly in coastal and estuarine regions where climate change drives significant changes in salinity patterns. Melting polar ice caps, altered precipitation patterns, and rising sea levels contribute to unpredictable variations in salinity, which impact species sensitive to these changes. Systems must prioritise species selection and technological solutions to maintain productivity under such conditions. Euryhaline species, which tolerate a wide range of salinity levels, are commonly favoured in these environments. For example, tilapia and sea bass exhibit strong resilience to salinity fluctuations, making them ideal candidates for aquaculture in variable environments (Tine et al., 2014; Rahman et al., 2021).

Technological interventions, such as selective breeding programs, have advanced the development of strains with enhanced tolerance to salinity. Research into Tilapia has shown the potential for breeding salt-tolerant variants capable of thriving in environments affected by salinity intrusion (Yue et al., 2024). Furthermore, closed systems like Recirculating Aquaculture Systems (RAS) offer controlled environments where salinity levels can be adjusted to meet species-specific requirements, reducing stress and enhancing growth rates. Innovations in water filtration and desalination technologies also allow operators to mitigate the impacts of salinity fluctuations effectively (Martins et al., 2010).

Examples of adaptive aquaculture practices include operations in Bangladesh that have shifted to salt-tolerant species in response to increasing coastal salinity. These practices have minimised economic losses and bolstered food security in vulnerable regions (Troell et al., 2023). By prioritising adaptability, aquaculture systems can better withstand the dynamic challenges posed by global warming, ensuring sustainable production and resilience.

Economic Viability and Scalability

The economic viability and scalability of advanced aquaculture systems are vital to ensuring widespread adoption. While systems like RAS and IMTA offer long-term benefits, their high upfront costs can deter small- and medium-scale operators. Cost-sharing mechanisms, such as public-private partnerships and government subsidies, can address financial barriers. Additionally, economies of scale achieved through larger operations or cooperative models can reduce per-unit costs. Studies indicate that scaling IMTA systems in Canada increased production efficiency by 25% while significantly improving environmental outcomes (Baltadakis, 2021). Innovations in modular aquaculture systems, which allow gradual expansion, provide flexible and cost-effective solutions for new entrants to the industry.

3. Innovative Systems Addressing Climate Challenges

Innovative aquaculture systems, such as offshore aquaculture, RAS, and IMTA, present viable solutions to combat climate-induced challenges. Offshore aquaculture reduces risks from eutrophication and hypoxia by operating in stable deep-water environments, while RAS provides precise environmental control, minimising external impacts. IMTA enhances ecological resilience by integrating complementary species, improving nutrient recycling and water quality (Holmer, 2010; Pereira et al., 2024). These technologies demonstrate the potential for sustainable aquaculture practices that align with environmental and economic goals.

Offshore Aquaculture

Offshore aquaculture has emerged as a promising solution to address climate-induced challenges in coastal and nearshore systems. Operating in deeper waters, these systems benefit from stable temperature profiles, higher oxygen levels, and reduced nutrient accumulation, mitigating risks associated with eutrophication and hypoxia (Holmer, 2010). Offshore cages, such as those used for gilthead seabream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) in the Mediterranean, demonstrate the potential of these systems to expand aquaculture production while minimising environmental impacts (Nielsen et al., 2021). However, offshore systems require significant investment in robust infrastructure to withstand strong currents and wave action, as well as advanced monitoring technologies to ensure operational efficiency.

Recirculating Aquaculture Systems (RAS)

RAS minimises water usage and allows for precise environmental control, reducing impacts from external climate fluctuations (Martins et al., 2010). Recirculating Aquaculture Systems (RAS) represent a cutting-edge approach to addressing environmental and resource constraints. These closed systems recycle water within controlled environments, significantly reducing water usage and limiting the impact of external environmental fluctuations (Badiola et al., 2012). RAS allows for precise control over temperature, oxygen levels, and waste management, making it suitable for species sensitive to environmental changes. For instance, salmon farming in Norway increasingly relies on RAS to mitigate the effects of warming coastal waters. However, the high energy demands and operational costs of RAS necessitate continued innovation to enhance energy efficiency and economic viability (Martins et al., 2010).

Integrated Multi-Trophic Aquaculture (IMTA)

IMTA enhances ecological resilience by integrating species with complementary functions, such as fish, shellfish, and seaweed (Pereira et al., 2024). Integrated Multi-Trophic Aquaculture (IMTA) is an innovative system that incorporates multiple species from different trophic levels in a single farming operation. This system leverages the natural ecological relationships between species to improve nutrient cycling and reduce environmental impacts. For example, seaweed and bivalves can absorb excess nutrients generated by finfish production, mitigating eutrophication and improving water quality (Pereira et al., 2024). In Canada, IMTA systems incorporating Atlantic salmon (*Salmo salar*), mussels (*Mytilus edulis*), and kelp (*Saccharina latissima*) have demonstrated ecological and economic benefits, including increased biomass production and reduced nutrient loads in surrounding waters (Troell et al., 2003).

Seaweed Aquaculture

Seaweed farming is gaining recognition as a climate-resilient aquaculture system with substantial environmental benefits. Seaweeds absorb carbon dioxide and nutrients from the water, countering ocean acidification and eutrophication. Additionally, seaweed cultivation has been proposed as a carbon sequestration strategy to mitigate the impacts of climate change (Froehlich et al., 2019). In Asia, large-scale seaweed farms significantly contribute to local economies while enhancing marine ecosystem health. Emerging technologies, such as offshore seaweed farming platforms, further expand the potential for sustainable seaweed production in regions with limited coastal space (Visch et al., 2023).

4.5 Smart Aquaculture Technologies

The integration of digital technologies, such as artificial intelligence (AI), the Internet of Things (IoT), and remote sensing, has revolutionised aquaculture operations. Smart systems enable real-time monitoring of environmental parameters, including temperature, salinity, and dissolved oxygen, allowing farmers to respond proactively to changing conditions (Føre et al., 2018). For example, automated feeding systems and AI-driven health diagnostics enhance operational efficiency while reducing waste. These innovations support the sustainability and scalability of aquaculture systems in the face of climate change pressures.

4. Policy and Economic Considerations

The adoption of climate-resilient aquaculture systems requires comprehensive policy support and economic frameworks. Regulatory incentives, such as subsidies and grants, can offset high initial costs, while international collaborations and market-driven demand for sustainable products drive industry transformation. Certification schemes and eco-labels provide economic incentives for environmentally responsible practices. Additionally, insurance mechanisms tailored to climate risks ensure operational continuity for vulnerable stakeholders (FAO, 2020; Bush et al., 2013). These considerations are crucial for aligning aquaculture practices with global sustainability goals.

Regulatory Support

Governments play a pivotal role in fostering climate-resilient aquaculture systems. Policies should prioritise incentives for adopting sustainable technologies such as Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA). For instance, the European Union's Common Fisheries Policy (CFP) promotes sustainable aquaculture by integrating climate adaptation strategies (FAO, 2020). Subsidies, tax breaks, and grants can further encourage investments in innovative systems. Additionally, regulatory frameworks must address issues such as water use efficiency, waste management, and disease control to align aquaculture practices with environmental sustainability goals (OECD, 2021).

Economic Feasibility

The high initial costs of advanced systems, like RAS and IMTA, must be offset by long-term benefits, including reduced losses from climate-related impacts (Tett et al., 2011). The transition to advanced aquaculture systems often entails high initial costs, which can deter widespread adoption, particularly in low- and middle-income regions. A cost-benefit analysis is essential to demonstrate the long-term economic advantages of climate-resilient systems, including reduced losses from environmental and disease-related disruptions. For example, RAS reduces dependency on external water sources and minimises environmental risks, leading to lower operational costs over time (Badiola et al., 2012). Public-private partnerships and financial assistance programs can bridge funding gaps, ensuring broader accessibility to these technologies (World Bank, 2013).

4.1. International Collaboration and Consumer Awareness

Climate change impacts transcend national borders, necessitating international cooperation. Collaborative research initiatives, such as those under the Horizon Europe framework, focus on developing climate-resilient aquaculture technologies and sharing best practices among stakeholders (European External Action Service, 2021). Moreover, international organisations, such as the Food and Agriculture Organization (FAO), provide technical support and policy recommendations to strengthen global aquaculture resilience (FAO, 2024). Regional alliances, such as the Asia-Pacific Fishery Commission (APFIC), also facilitate knowledge transfer and resource pooling, enabling countries to adopt tailored solutions for their unique challenges (APFIC, 2019). Global partnerships can facilitate knowledge sharing and funding for research into climate-resilient aquaculture practices (Tett et al., 2011).

Market Dynamics

Market forces play a pivotal role in driving the adoption of sustainable aquaculture practices. Rising consumer demand for environmentally friendly seafood has created economic incentives for producers to implement sustainable systems. Certification schemes, such as those offered by the Aquaculture Stewardship Council (ASC), provide market advantages by enhancing competitiveness and offering transparency to consumers, fostering industry-wide shifts toward sustainability (Bush et al., 2013). These certifications, combined with educational campaigns that highlight the environmental benefits of climate-adaptive practices such as Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA), significantly influence purchasing behaviour, encouraging a market shift toward eco-friendly seafood (Potts et al., 2021). In addition, digital technologies, including blockchain, are transforming the seafood supply chain by enabling traceability, fostering trust, and ensuring accountability among consumers and producers (Probst, 2020). By integrating certification schemes, educational efforts, and technological advancements, the aquaculture industry is progressively aligning with sustainability goals, ensuring both environmental and economic benefits.

Risk Mitigation and Insurance Mechanisms

As climate-related risks, such as extreme weather events and disease outbreaks, increase in frequency and intensity, robust risk mitigation strategies and tailored insurance mechanisms are critical for protecting aquaculture operations. Insurance products designed explicitly for aquaculture, such as crop insurance for aquaculture species or parametric insurance for weather-related damage, can provide financial security to operators. Collaboration between governments, financial institutions, and insurance providers is necessary to develop affordable and accessible insurance schemes. For instance, parametric insurance programs in the Philippines have successfully provided payouts to fish farmers affected by typhoons, enabling quick recovery and continuity of operations (Van Anrooy et. al., 2022). Risk assessment tools, such as climate modelling and early-warning systems, further enhance resilience by helping operators anticipate and mitigate potential disruptions (Allison et al., 2009).

Summary

The impacts of global warming on aquaculture underscore the need for strategic system selection and sustainable practices to ensure the industry's long-term resilience and productivity. As climate-induced challenges such as rising temperatures, ocean acidification, and disease proliferation continue to intensify, adopting innovative and adaptive aquaculture systems becomes imperative. This chapter has highlighted critical approaches, including Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and offshore aquaculture, as viable solutions to mitigate these challenges.

Recirculating Aquaculture Systems (RAS) provide precise environmental control, enabling operations to withstand external climatic fluctuations while reducing dependency on external water sources. Integrated Multi-Trophic Aquaculture (IMTA) promotes nutrient recycling and ecosystem stability, offering a holistic approach to sustainability. Offshore aquaculture, operating in deeper and more stable waters, minimises the impacts of coastal eutrophication and hypoxia, providing an effective alternative for expanding production.

The transition to these systems requires comprehensive policy frameworks and financial incentives to overcome the barriers associated with high initial costs. Governments, private stakeholders, and international organisations must collaborate through mechanisms such as international agreements, funding programs, and knowledge-sharing platforms. Specific measures, including subsidies, tax breaks, and grants, will be crucial in encouraging investments in climate-resilient technologies, particularly for small-scale farmers who are most vulnerable to climate-related shocks.

Consumer awareness and market demand for environmentally sustainable seafood products create additional opportunities for industry transformation. Certification schemes and eco-labels can incentivise producers to adopt climate-resilient practices while fostering trust and transparency among consumers. Educational campaigns and global scaling of these initiatives can further enhance their impact, particularly in regions with high aquaculture potential. Leveraging technologies such as blockchain for supply chain traceability will also play a vital role in fostering consumer confidence.

Looking ahead, investments in research and development are crucial for innovating and refining aquaculture systems. Prioritised areas include improving energy efficiency in RAS, developing low-cost IMTA systems, and advancing pathogen control strategies. Long-term environmental monitoring and proactive management strategies will ensure adaptability to the evolving realities of climate change.

By integrating technological advancements and ecological principles, the aquaculture sector can enhance resilience and sustainability. Policymakers, researchers, and industry stakeholders must act decisively to implement systems that ensure the sector's long-term viability in the face of a changing climate. Through a collective effort, aquaculture can continue to thrive, contributing to global food security and economic development in an era of climate change.

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Glossary

Acidification – a process where water pH decreases, making it more acidic. In oceans, this primarily occurs due to CO_2 absorption from the atmosphere.

Adaptation – adjustment to changing environmental conditions, occurring through natural evolution or technological interventions (e.g., selective breeding for heat resistance).

Aerobic process – chemical or biological processes that occur in the presence of oxygen.

Anaerobic conditions – environments with very little or no oxygen, such as the bottom of ponds or wetlands. Under such conditions, organic matter decomposes without oxygen, often releasing gases such as methane.

Animal welfare – ethical consideration for the living conditions, health, and natural behaviour expression of farmed fish and aquatic animals in aquaculture systems.

Aquaculture – the breeding, cultivation, and harvesting of fish, crustaceans, molluscs, and aquatic plants in controlled conditions. It is essentially farming in water, for food, conservation, or other commercial and environmental purposes.

Aquatic ecosystem – a water-based environment where living organisms interact with each other and with the physical surroundings.

Biodiversity – the variety of plants, animals, and microorganisms in a given area or ecosystem. It is essential for healthy ecosystem functioning, as each species contributes to ecological balance.

Biofilter – a filtration system using living organisms (e.g., bacteria) to break down waste in aquaculture systems.

Biosecurity – measures taken to prevent the introduction and spread of harmful organisms, such as pathogens, in aquaculture systems.

Carbon dioxide emissions – the release of CO_2 and other greenhouse gases into the atmosphere, primarily from fossil fuel combustion.

Carbon footprint – the total amount of greenhouse gases (mainly CO_2, but also methane and nitrous oxide) produced by human activities, product manufacturing, or services. It helps assess the climate impact of actions such as transport, energy use, food production, or industry. A smaller footprint means a lower environmental impact.

Carbon sequestration – the process of capturing and storing atmospheric CO_2, often through natural means such as seaweed cultivation.

Climate change – long-term global or regional climate shifts linked to increased greenhouse gas concentrations in the atmosphere.

Clinical signs – visible symptoms of disease observed by a veterinarian or specialist (e.g., redness, abnormal swimming).

Closed RAS – a system where water is recycled in a controlled environment, reducing water use and environmental impact.

CRISPR–Cas9 – a revolutionary gene-editing tool that enables precise modification of DNA sequences to enhance traits in aquaculture species, such as disease resistance or growth rate.

Dead zones – water areas with critically low oxygen levels (often due to eutrophication) where most marine life cannot survive.

Denitrification – an anaerobic process in which chemotrophic bacteria convert nitrates (NO_3) into nitrogen gas (N_2), nitrous oxide (N_2O), or ammonia (NH_3).

Diagnosis – identification of the nature of a disease; diagnostic – related to diagnosis.

Differential diagnosis – distinguishing between multiple possible diseases to determine the actual cause.

Disease outbreak – the rapid spread of disease, often driven by higher temperatures and poor water quality.

Ecosystem integrity – the capacity of an ecosystem to maintain its structure, functions, and processes while supporting biodiversity and ecological interactions.

Ecosystem services – benefits humans obtain from natural ecosystems, such as food provision, water purification, and carbon sequestration. Sustainable aquaculture aims to preserve or enhance these services.

Euryhaline species – organisms that can tolerate a wide range of salinities and adapt to changing environments.

Eutrophication – the process in which excessive nutrients, especially nitrogen and phosphorus, enter water bodies, triggering algal blooms, reducing water clarity, and oxygen depletion, harming aquatic organisms and ecosystem stability.

Feed conversion ratio – the amount of feed required to produce a certain amount of body mass in aquaculture animals.

Feed efficiency ratio – the ratio of growth to the amount of feed consumed.

Filter feeders – aquatic organisms, such as crustaceans, that feed by filtering fine particles from the water and help improve water quality.

Global warming – the rise in average surface temperature of the Earth due to increasing greenhouse gas concentrations, leading to sea level rise, extreme weather, and ecosystem changes.

Greenhouse gases – gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) that trap heat in the atmosphere and contribute to global warming and climate change.

Gross energy – the total energy contained in feed.

Harmful algal bloom – a rapid increase in algae that produce toxins or reduce oxygen levels, harming aquatic life and human health.

Hypoxia – a state of low dissolved oxygen in water, insufficient for most aquatic organisms to survive. Often caused by eutrophication or high temperature and thermal stratification.

Infection – the invasion and multiplication of pathogenic organisms in body tissues.

Integrated Multi-Trophic Aquaculture – co-cultivation of different species (e.g., fish, crustaceans, seaweeds) to recycle nutrients and reduce environmental impact.

Life Cycle Assessment – a method used to evaluate environmental impacts from raw material extraction to the final product.

Marker-assisted selection – a biotechnological method that uses genetic markers to select individuals with desired traits for breeding, enhancing the efficiency of selective breeding.

Metabolic rate – the speed at which an organism uses energy to sustain physiological functions; in fish, it increases with temperature and oxygen demand.

Mitigation strategies – actions to reduce the adverse effects of climate change or environmental changes (e.g., reducing CO_2 emissions, implementing sustainable practices).

MO diet – multi-objective optimisation considering ecological, economic, and other factors simultaneously.

Net energy – energy available to the organism.

Net zero – the balance between the amount of greenhouse gases produced and the amount removed from the atmosphere.

Nitrification – an aerobic process in which bacteria convert ammonia (NH_4^+) to nitrates (NO_3^-).

Nutrient cycle – the movement of nutrients through an ecosystem; IMTA systems often enhance this cycle.

Nutrient loading – excessive input of nitrogen and phosphorus into water bodies from agriculture, domestic, or industrial sources, causing ecological imbalance.

Ocean acidification – the reduction of ocean pH due to excessive atmospheric CO_2 absorption, which affects calcifying organisms like molluscs and corals.

Offshore aquaculture – aquaculture systems installed further from the shore, where environmental conditions are more stable and ecological impact is lower.

Oxygen deficiency – a condition of very low or absent dissolved oxygen in water, making it uninhabitable for many aquatic animals.

Pathogen – a microorganism (e.g., bacterium, virus, parasite) capable of causing disease in aquatic organisms.

Phenotypic plasticity – the ability of an organism to adjust to environmental changes by altering its physiology, morphology, or behaviour (e.g., in response to temperature or salinity).

Prebiotic supplement – food products (usually high in fibre) that serve as nutrition for animal microbiota.

Prebiotics – fibre-based dietary supplements that promote the growth of beneficial gut microorganisms.

Probiotic supplement – food products or supplements containing live microorganisms.

Probiotics – live microorganisms that, when consumed in sufficient quantities, improve gut flora and support host health. They can be found in food or dietary supplements.

Quarantine – isolation or movement restriction to prevent the spread of infectious disease.

Recirculating Aquaculture Systems – closed-loop systems where water is continuously filtered and reused, allowing precise environmental control and water conservation.

Resilience – the ability of a species or ecosystem to survive, recover structure and functions after environmental disturbances or stressors, including climate change.

Salinity fluctuations – changes in the salt concentration of water bodies due to precipitation, glacier melt, or human activity, affecting the survival of aquatic organisms.

Seaweed aquaculture – the cultivation of seaweed for CO_2 absorption, nutrient removal, and sustainable food production.

Selective breeding – the process of choosing parent organisms with desirable traits to produce offspring with similar or improved characteristics (e.g., faster growth or disease resistance).

Smart aquaculture – the use of advanced technologies (e.g., AI, IoT, sensors) to manage and optimise aquaculture systems.

Sustainable management practices – methods aimed at balancing environmental, economic, and social factors for the long-term conservation of natural resources.

Thermal stratification – formation of temperature layers in a water body that hinder vertical movement of nutrients and oxygen, potentially causing hypoxic conditions.

Thermal stress – physiological stress resulting from water temperatures outside an organism's optimal range, affecting growth or reproduction.

Transgenic species – genetically modified organisms with inserted genes from other species. In aquaculture, these may grow faster or have higher disease resistance.

Trophic levels – the hierarchical levels in a food chain, through which energy flows from primary producers (e.g., plants or algae) to consumers (herbivores, predators) and decomposers.

UV sterilisation – the use of ultraviolet light to kill pathogens in water, particularly in RAS systems.

Vaccine – a biological preparation designed to build or boost immunity against specific diseases.

***Vibrio* spp.** – a group of bacteria thriving in warm waters, known to cause diseases in fish and shrimp.

Water quality – physical, chemical, and biological characteristics of water that determine the health and productivity of aquatic organisms.

Water scarcity – a situation where water resources are insufficient to meet ecological and human demands, especially under climate change and intensive use.