CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT

GLOBAL ISSUES & LOCAL PERSPECTIVES

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue **Climate smart actions (CSA) aquaculture, agroforestry and resources management** necessary in policy making process that will stimulate increase in food production and environmental sustainability. **Climate smart actions (CSA) aquaculture, agroforestry and resources management :** ***Global Issues & Local Perspectives*** is organized in three parts. Part One deals with The Concept of **Climate smart actions (CSA)**, Part Two is concerned with The Concept of **aquaculture,** and Part Three deals with the Concept of **agroforestry and resources management**

Eteyen Nyong; March 2026

Chapter 13:

Climate-Smart Hatchery Management as Climate Smart Action (CSA): Sustainable Breeding, Larval Rearing, and Fish Health in Aquaculture Systems

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1.0 Introduction

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Aquaculture has emerged as one of the fastest-growing food production sectors worldwide, outpacing many terrestrial livestock systems due to its rapid expansion and increasing contribution to global food security (Mbaka *et al.,* 2022). In 2022, global aquaculture production reached unprecedented levels, surpassing capture fisheries in aquatic animal output for the first time and accounting for more than half of all fish consumed by humans, a trend that emphasizes its central role in meeting the rising demand for high-quality protein, essential nutrients, and livelihoods (FAO, 2024; OECD/FAO, 2025; Samy-Kamal, 2025).

At the heart of aquaculture systems are hatcheries, which provide the foundation for sustainable production by supplying high-quality eggs, larvae, juveniles, and seedstock for fish, shrimp, and shellfish production (Akinjogunla and Usman, 2023). Reliable hatchery output is critical for ensuring consistent supply, optimizing growth performance, reducing reliance on wild seed sources, and supporting the resilience of aquaculture value chains, especially in developing countries where access to quality seed remains constrained (Zhu *et al*., 2024; Cortes *et al*., 2026).

Given its pivotal role in food security, nutrition, and economic development, particularly in low - and middle - income countries, strengthening hatchery management represents a strategic priority for sustaining the continued growth and ecological sustainability of aquaculture into the coming decades (Simasiku *et al*., 2024).

However, hatcheries are among the most vulnerable components of aquaculture due to the narrow physiological tolerances of early life stages and their sensitivity to environmental fluctuations (Dai *et al*., 2025; Haque *et al*., 2025).

Climate change exacerbates these vulnerabilities, manifesting as rising water temperatures, ocean acidification, hypoxia, salinity fluctuations, and the emergence of novel pathogens. These stressors increase mortality, reduce growth and reproductive performance, and alter larval quality, ultimately threatening aquaculture productivity and economic viability (Okon *et al.*, 2023; Jeyachandran, 2025).

Early life stages are particularly sensitive: eggs and larvae are prone to temperature-induced mortality, acidification-related deformities, and pathogen infections, while broodstock reproductive performance and gamete quality are affected by prolonged stress (Ajayi *et al*., 2024).

In response to these challenges, climate-smart hatchery management (Figure 1) has emerged as a transformative approach. It integrates adaptive breeding, advanced larval rearing techniques, disease management, renewable energy adoption, and sustainable operational practices to enhance resilience, productivity, and environmental stewardship.

Figure 1. Use of IoT devices in aquaculture.
Source: The Edge, Malaysia (2025)

Climate-smart hatcheries aim to:

a) maintain optimal environmental conditions despite climatic fluctuations
b) produce genetically robust seed with improved tolerance to thermal, osmotic, and disease stress
c) reduce climate-driven disease outbreaks and mortality
d) lower carbon footprint and resource use through renewable energy and efficient water management

This chapter explores the state – of – the - art innovations in hatchery management designed to mitigate climate risks, enhance larval and broodstock resilience, and support sustainable aquaculture. It synthesizes strategies across breeding, larval rearing, disease control, and operational sustainability, highlighting practical applications and case studies from tilapia, shrimp, and salmon hatcheries worldwide. By integrating technological, ecological and genetic solutions, climate-smart hatcheries provide a blueprint for maintaining reliable seed production and safeguarding aquaculture in an era of accelerating climate change.

1.1 Aims and Objectives of the Chapter

The aim of this chapter is to provide a comprehensive synthesis of innovations and strategies in climate-smart hatchery management that enhance resilience, sustainability, and productivity in aquaculture.

Specifically, the chapter objectives are to:

a) identify and characterize climate-related stressors affecting eggs, larvae, and broodstock in hatchery systems.

b) evaluate breeding innovations for climate resilience, including selective breeding, temperature-adaptive broodstock management, genomic selection, and gene editing.

c) review advanced larval rearing techniques such as precision environmental control, biofloc and green water systems, microbiome modulation, and optimized nutrition.

d) examine climate-smart disease control strategies, including vaccination, immunostimulants, digital diagnostics, and biosecurity measures.

e) explore renewable energy and low-carbon operational practices to enhance energy efficiency, reduce greenhouse gas emissions, and increase operational resilience.

f) highlight sustainability and environmental considerations, including efficient water use, nutrient management, environmental monitoring, and ecosystem-based hatchery siting.

g) present case studies and practical applications demonstrating the integration of these approaches across tilapia, shrimp, and salmon hatcheries globally.

By meeting these objectives, the chapter provides a holistic framework for designing and managing hatcheries that are resilient to climate change, environmentally sustainable, and capable of sustaining high - quality seed production to support global aquaculture growth.

2.0 Climate Change and Hatchery Vulnerabilities

Hatcheries are among the most climate-sensitive components of aquaculture, as early life stages of fish, shrimp and shellfish have narrow physiological tolerances (Hague *et al.*, 2025). Climate change intensifies multiple environmental stressors (Figure 2) including rising temperatures, acidification, hypoxia, salinity fluctuations, and the emergence of pathogens which directly impact survival, growth, and reproductive performance (Mitra, 2023).

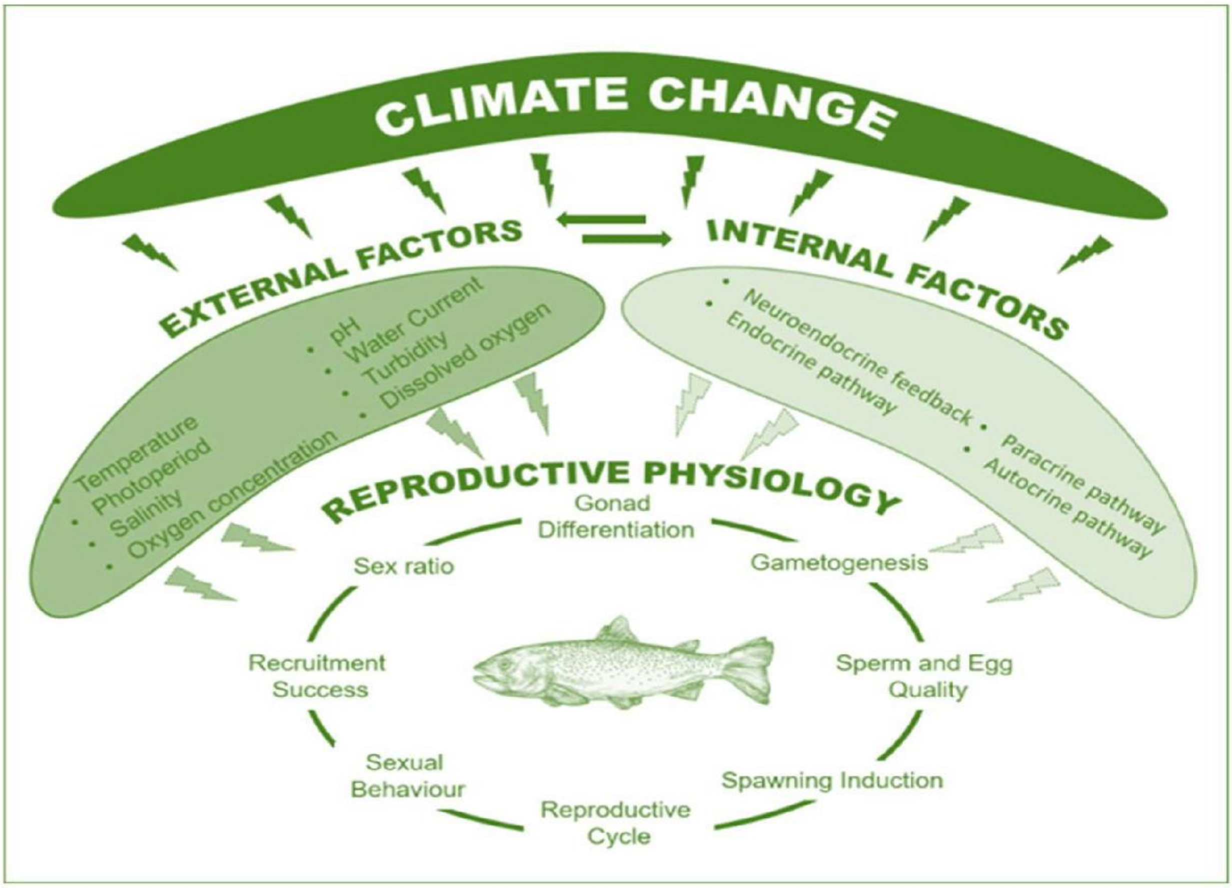

Figure 2: External and internal climate-dependent factors that affect fish reproductive physiology. Source: Mitra, A. (2023).

Eggs, larvae, and broodstock respond differently to these stressors, making it critical to identify stage-specific vulnerabilities to design effective climate-smart interventions (Torsabo *et al*., 2024; Akande & Oyarekhua, 2025; Haque *et al*., 2025). Table 1 below summarizes the key climate stressors and their impacts across hatchery stages, highlighting where targeted management strategies are most needed.

Table 1: Climate Stressors and Their Impact on Hatchery Stages

Climate Stressor	Hatchery Stages			Mechanism
	Egg	**Larval**	**Broodstock**	
Temperature rise / heat stress	↓ Hatchability; developmental abnormalities	↑ Mortality; impaired feeding; deformities	↓ Gamete quality; reduced spawning frequency	Elevated temperatures accelerate metabolism, induce oxidative stress, and disrupt endocrine regulation. Heatwaves exacerbate mortality in sensitive early stages (Canosa & Bertucci, 2023).
Acidification / low pH	Shell deformities in mollusks	Weak exoskeleton or skeletal structure; reduced survival	Reduced fecundity and impaired gametogenesis	Lower carbonate availability affects shell and skeletal formation; acid stress alters metabolic and physiological processes (Wright-Fairbanks *et al.*, 2025).
Low dissolved oxygen (DO / hypoxia)	Embryo mortality; delayed development	Slow growth; impaired swimming and feeding; increased stress susceptibility	Stress, reduced reproductive performance	Hypoxia reduces ATP production and impairs organ development; high-density tanks exacerbate effects (Yan *et al.*, 2025).
Salinity fluctuations	Osmoregulatory failure; abnormal development	Reduced growth, osmotic stress, higher mortality	Stress; impaired gonadal development	Abrupt salinity changes affect ion balance, metabolism, and larval osmoregulatory capacity (Dildar *et al.*, 2025).
Pathogen emergence / disease	Infection reduces egg viability	High mortality; deformities; stunted growth	Reduced spawning efficiency; increased susceptibility	Warming and water quality stress favor pathogen proliferation; larvae are immunologically naïve (Scanes *et al.*, 2025).

Climate Stressor	Hatchery Stages			Mechanism
	Egg	Larval	Broodstock	
Harmful algal blooms (HABs)	Toxin exposure reduces viability	Mortality; reduced feeding efficiency; impaired immunity	Stress and reduced reproductive performance	HAB toxins can bioaccumulate in rearing water, affecting development and immune function (Brenckman *et al*., 2025).
High ammonia / nitrogen accumulation	Toxicity reduces embryo survival	Growth inhibition; gill damage; stress	Stress; reduced reproductive output	Nitrogenous waste accumulates rapidly under poor water exchange; impacts metabolism and immune function (Edwards *et al*., 2025).
Extreme weather / flooding	Mechanical damage; temperature/salinity shocks	Mortality; reduced feeding; stress	Stress; disrupted spawning cycles	Sudden environmental changes can overwhelm adaptive capacity; risk higher in open or semi-closed systems (Saeed *et al*., 2023)

**** ↓- decreases; ↑ - increases*

The table demonstrates that each hatchery stage is uniquely vulnerable: eggs are particularly sensitive to temperature, acidification, and hypoxia; larvae are highly susceptible to pathogen proliferation, water quality instability, and extreme environmental fluctuations; while broodstock reproductive performance and gamete quality are compromised under prolonged thermal and chemical stress.

These vulnerabilities accentuate the urgency of implementing climate-smart hatchery strategies, including adaptive breeding, precision environmental control, biofloc and green water systems, microbiome modulation, and robust biosecurity. By understanding stage-specific stressors, hatchery managers can prioritize interventions that mitigate mortality, stabilize seed quality, and enhance resilience under changing climate conditions, providing a strong foundation for the innovations discussed in the subsequent sections.

3.0 Innovations in Climate-Smart Broodstock and Breeding Management

Climate-smart broodstock and breeding management are pivotal for enhancing the resilience of aquaculture systems in the face of climate variability (Maulu *et al*., 2021). Hatchery stages are highly sensitive to environmental stressors, and genetic improvement offers a powerful means to buffer fish, shrimp, and shellfish against heat, salinity fluctuations, disease outbreaks, and other climate-driven challenges (Hague *et al*., 2025; Jeyachandran, 2025).

Modern breeding strategies integrate traditional selection (Table 2) with advanced genomics, biotechnology, and environmental conditioning to produce robust seed that can thrive under changing climate conditions.

Table 2: Breeding Innovations for Climate - Resilient Aquaculture

Approach	Target Trait / Focus	Species	Benefits
Selective breeding	Heat tolerance; salinity tolerance; growth performance	Tilapia, Catfish	Higher survival under temperature stress; improved growth; better feed efficiency
Genomic selection (GS)	Disease resistance; thermal tolerance; stress resilience	Salmon, Carp, Tilapia	Faster breeding cycles; improved accuracy; polygenic trait improvement
Marker-assisted selection (MAS)	Viral and bacterial resistance	Shrimp, Salmon	Reduced mortality; lower antibiotic use; targeted genetic gains
Temperature - adaptive broodstock selection	Reproductive performance at high temperature	Tilapia, Catfish, Shrimp	Stable gamete quality; improved spawning success under heat stress
CRISPR / gene editing	Heat tolerance, disease resistance, metabolic efficiency	Tilapia, Salmon, Shrimp	Rapid development of resilient strains; enhanced growth and stress tolerance
Hybridization / crossbreeding	Stress tolerance and growth	Tilapia, Catfish	Combines complementary traits from different strains; enhanced robustness

*** *CRISPR - Clustered Regularly Interspaced Short Palindromic Repeats*

3.1 Selective Breeding for Climate Resilience

Selective breeding remains a cornerstone of climate-smart hatcheries. According to Dildar *et al*., (2025), beyond traditional growth and feed efficiency traits, breeding programs increasingly target heat tolerance, salinity tolerance, and resistance to climate-sensitive diseases (Figure 3). Selective breeding enhances stage-specific resilience, particularly for larvae and juveniles, which are highly sensitive to thermal and osmotic stress.

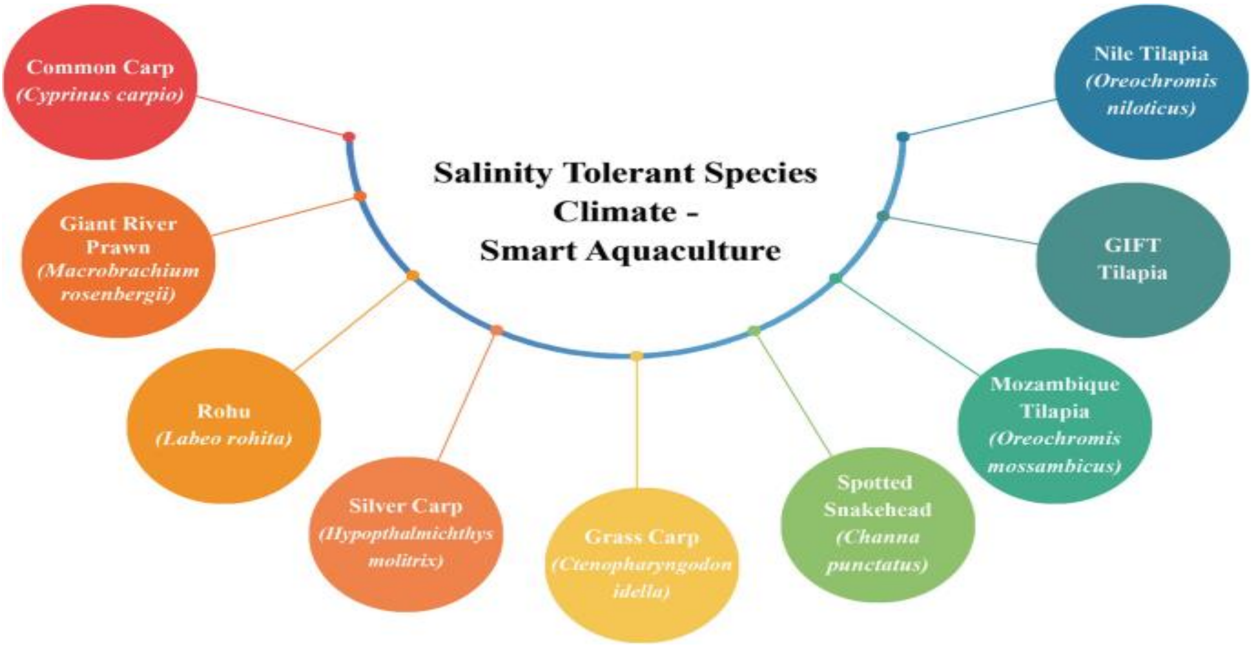

Figure 3: Climate – resilience species ideal for breeding
Source: Nayak *et al*., (2025).

3.2 Temperature - Adaptive Breeding

Temperature-adaptive breeding focuses on reproductive performance under elevated and fluctuating temperatures. Strategies include:

a) Broodstock selection: Choosing individuals that maintain fecundity, spawning frequency, and gamete quality at high temperatures.

b) Thermal conditioning: Exposing broodstock to controlled temperature cycles to enhance physiological plasticity.

c) Thermal refugia: Utilizing shading, cooling, or water exchange systems to stabilize reproductive environments.

This approach improves hormonal stability, gamete quality, and larval survival, ensuring consistent seed production during heatwaves and seasonal extremes (Mitra *et al*., 2023; Lema *et al*., 2024).

3.3 Genomic and Biotechnological Approaches

Modern genomic tools accelerate climate-resilient breeding by increasing precision and speed:

i. Marker-assisted selection (MAS): Targets specific genes associated with resistance to viral and bacterial pathogens, such as WSSV in shrimp and *Streptococcus* infections in tilapia.

ii. Genomic selection (GS): Uses genome-wide markers to predict performance for polygenic traits like thermal tolerance, growth under stress, and disease resistance, enabling faster and more accurate breeding cycles.

iii. CRISPR and gene editing: Offers potential for targeted development of heat-tolerant, disease-resistant, and metabolically efficient strains, though regulatory and ethical considerations remain.

These tools allow hatcheries to proactively select for traits that confer resilience, reducing reliance on chemical treatments and supporting sustainable aquaculture production.

3.4 Hybridization and Crossbreeding

Hybridization combines complementary traits from different strains or species to enhance stress tolerance, growth, and robustness. This approach is especially useful in regions with highly variable climates, where hybrid offspring can perform better under fluctuating temperature, salinity, and water quality conditions (Xu *et al*., 2025).
By integrating selective breeding, temperature-adaptive approaches, genomics, and hybridization, climate-smart hatcheries can produce broodstock and larvae that are better equipped to withstand environmental stress, disease outbreaks and resource limitations (Ghorbanzadeh *et al*., 2025). These innovations lay the foundation for resilient seed production, reduced mortality and sustainable aquaculture in a changing climate (Torsabo *et al*., 2024).

4.0 Climate-Smart Larval Rearing Innovations

The larval stage is the most sensitive period in aquaculture, where survival, growth, and long-term performance are heavily influenced by environmental conditions (Siddique *et al*., 2023). Climate change aggravates these challenges by increasing water temperature variability, hypoxia, acidification, and pathogen prevalence, which collectively reduce larval survival and robustness (Abalasei *et al*., 2025). Climate-smart larval rearing innovations as shown in table 3 integrates precision environmental control, ecological engineering, microbiome management, and improved nutrition to enhance resilience, optimize growth, and reduce mortality.

Table 3. Climate-Smart Larval Rearing Innovations

Innovation	Function	Benefits
Precision environmental control (automated aeration, IoT sensors, AI)	Maintain optimal temperature, DO, pH, ammonia	Reduced stress and mortality; improved growth; enhanced survival under variable climates
Green water systems	Microalgae-based water stabilization and nutrition	pH buffering; natural feed; reduced cannibalism; improved larval vigor
Biofloc technology (BFT)	Microbial balance; nutrient recycling	Improved immunity; lower water use; reduced disease incidence; lower carbon footprint
Probiotics & microbiome modulation	Enhance digestion and immune function	Stress tolerance; reduced antibiotic dependence; higher survival
Improved larval nutrition	Microencapsulated feeds, enriched rotifers, microalgae	Enhanced FCR; better growth; improved stress resilience

**** IoT – Internet of Things; AI – Artificial Intelligence; DO – Dissolved Oxygen; pH – Hydrogen Concentration; FCR – Feed Conversion Ratio*

Climate-smart larval rearing integrates technological, ecological, and nutritional innovations to buffer larvae against climate-induced stress. By combining precision control, microbial engineering (Figure 4) and optimized nutrition, hatcheries can significantly improve survival, growth, and health of early life stages. These interventions not only mitigate climate-related risks but also contribute to more sustainable, resource-efficient, and resilient aquaculture systems. Precision feeding enhances feed conversion efficiency (FCR), reduces waste, and improves larval robustness, contributing directly to climate resilience (Karimanzira, 2025).

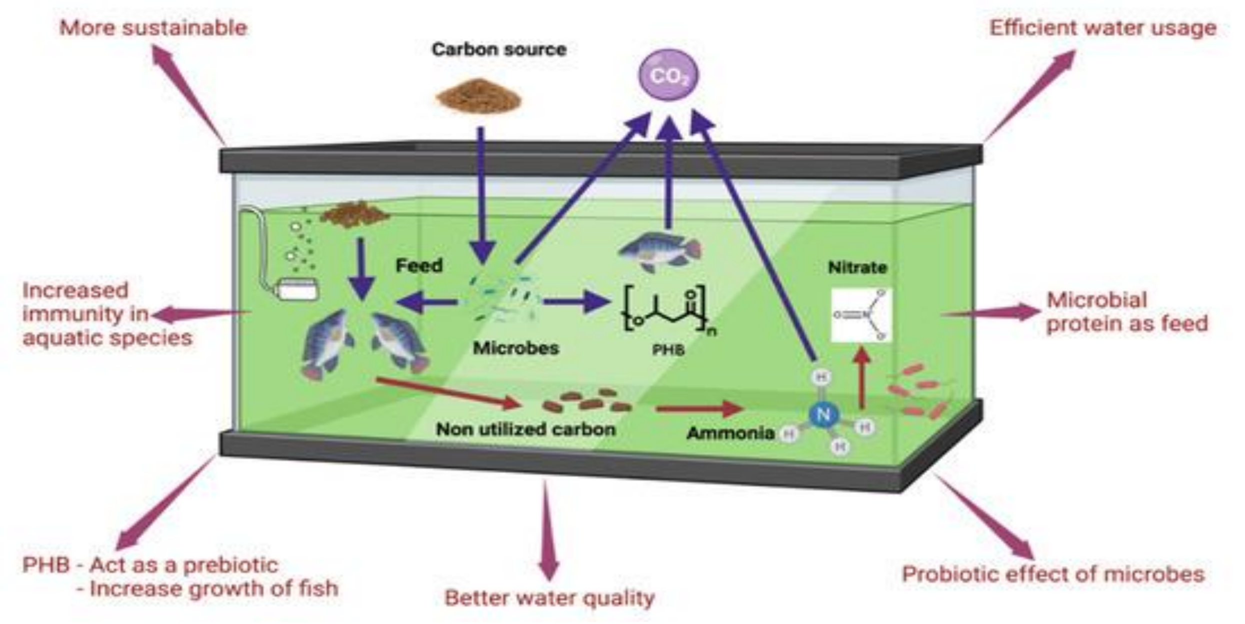

Figure 4: Flow diagram of the inputs and outputs of a generalized biofloc system.
Source: Padeniya *et al*., 2022

5.0 Disease Control in Climate-Smart Hatcheries

Climate change intensifies disease risks in aquaculture by altering pathogen dynamics, suppressing immune function, and creating favorable conditions for opportunistic infections (Combe *et al*., 2023). Elevated temperatures accelerate bacterial growth, while environmental stressors such as hypoxia, acidification, and salinity fluctuations compromise larval and broodstock immunity (Kari, 2025).

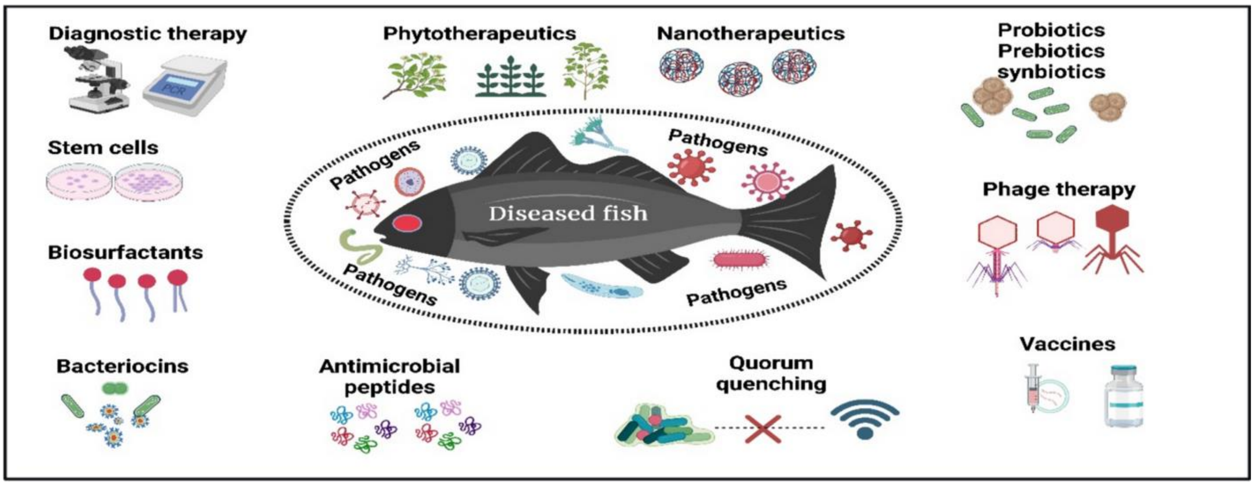

Figure 5: Alternative therapies for treating and controlling fish diseases
Source: Elgendy *et al*., 2024

Consequently, disease outbreaks become more frequent, severe, and economically damaging, particularly during sensitive early life stages. Climate-smart disease control (table 4) integrates preventive, diagnostic, and management strategies, aiming to reduce pathogen pressure, strengthen host resilience, and minimize reliance on antibiotics.

Table 4. Climate-Smart Disease Control Strategies

Strategy	Functions	Benefits
Vaccines (DNA, oral, immersion, nano-vaccines)	Prevent infection in juveniles and larvae	Reduced mortality; lower antibiotic use; improved immunity under thermal stress
Immunostimulants (β-glucans, herbal extracts, chitosan, peptides)	Enhance innate immunity	Improved stress tolerance; disease resistance; higher survival
Early detection (PCR, qPCR, AI surveillance, portable diagnostics)	Monitor pathogen presence and predict outbreaks	Timely intervention; reduced losses; improved preparedness
Biosecurity (RAS, UV/ozone treatment, vector control, movement restriction)	Prevent pathogen introduction and spread	Reduced infection rates; enhanced resilience; consistent seed production

**** DNA - Deoxyribonucleic Acid; PCR - Polymerase Chain Reaction; qPCR stands for Quantitative Polymerase Chain Reaction.AI - Artificial Intelligence; RAS - Renin–Angiotensin System; UV - Ultraviolet*

Climate-smart disease control combines preventive immunology, advanced diagnostics, and robust biosecurity to address the heightened pathogen risks posed by climate change (Jeyachandran, 2025). By integrating vaccines, immunostimulants, real-time monitoring, and proactive biosecurity measures, hatcheries can minimize disease-related losses, reduce antibiotic dependency, and maintain high-quality, resilient seed production (Carlino-Costa & Belo, 2025).

This integrated approach ensures that disease management supports both climate adaptation and sustainable aquaculture objectives, bridging the vulnerabilities identified in early life stages to the solutions provided by breeding, larval rearing, and operational innovations.

6.0 Integration of Renewable Energy and Low-Carbon Systems

Energy demand is a critical component of hatchery operations, as maintaining optimal water quality, temperature, aeration, and biosecurity require continuous power. Climate change worsens this demand through increased temperature stress, higher oxygen requirements, and expanded water treatment needs (Chapra *et al.*, 2021).

Simultaneously, reliance on fossil-fuel-based energy sources contributes to greenhouse gas emissions, undermining the sustainability of aquaculture systems. Climate-smart hatcheries address these challenges by integrating renewable energy and low-carbon technologies, improving both resilience and environmental performance (Bohnes, 2022; Jeyachandran, 2025).

6.1 Solar-Powered Aeration and Heating

Solar energy is increasingly deployed in hatcheries (Figure 6) to provide reliable, low-carbon power for critical operations:

a) Aeration systems powered by solar panels ensure stable dissolved oxygen levels, especially during heatwaves or periods of high larval density.

b) Heating broodstock or larval tanks using solar thermal energy maintains optimal reproductive and developmental conditions without relying on electricity or fossil fuels.

These solutions reduce operational costs, increase energy security, and provide resilience against grid instability, which is particularly important in tropical regions prone to power outages (Vo *et al.*, 2021; Mwakapoma *et al.*, 2025; Prasad *et al.*, 2025).

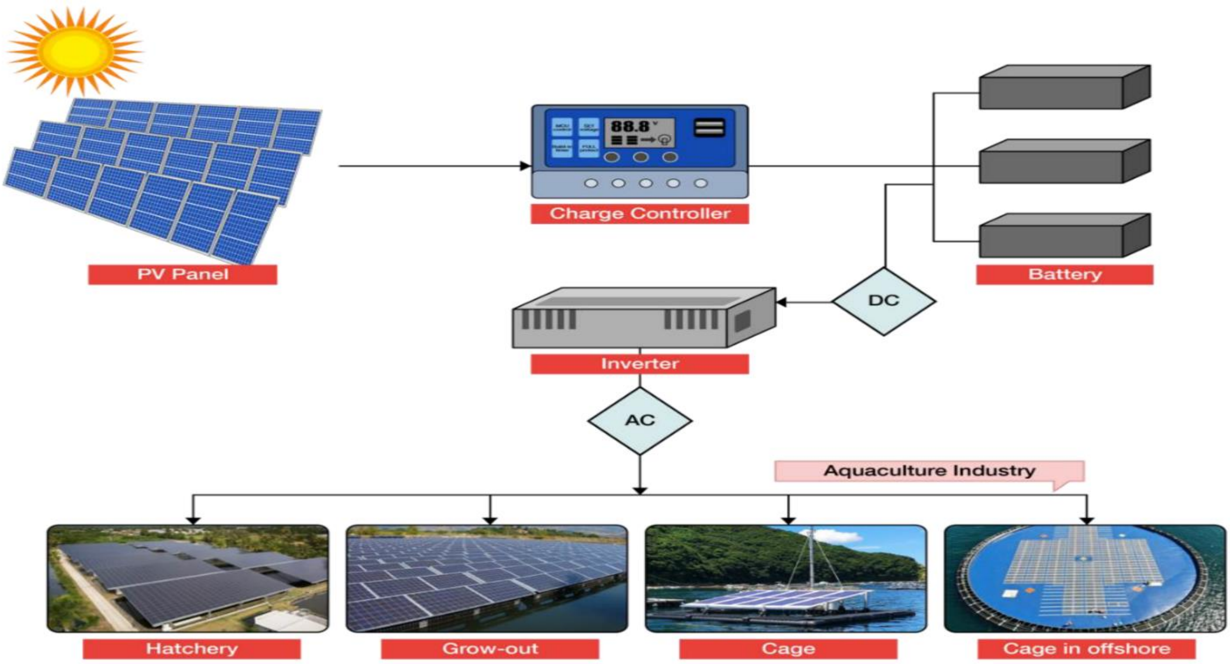

Figure 6: Application of Solar energy in Aquaculture
Source: Vo *et al.*, 2021.

6.2 Low-Energy Recirculating Aquaculture Systems (RAS)

Recirculating aquaculture systems (RAS) are widely adopted as climate-smart technologies (Figure 7):

a) Energy-efficient pumps, gravity-driven flows, and optimized biofilters reduce electricity consumption while maintaining high water quality.

b) Automated control systems minimize unnecessary energy use by adjusting flow, aeration, and filtration based on real-time water quality data.

c) Water recirculation decreases freshwater withdrawals and mitigates the effects of climate-induced water scarcity.

Low-energy RAS not only enhance hatchery resilience under variable climatic conditions but also reduce carbon emissions per unit of seed produced, supporting broader climate mitigation goals (Benjamin *et al*., 2022; Gupta *et al*., 2024).

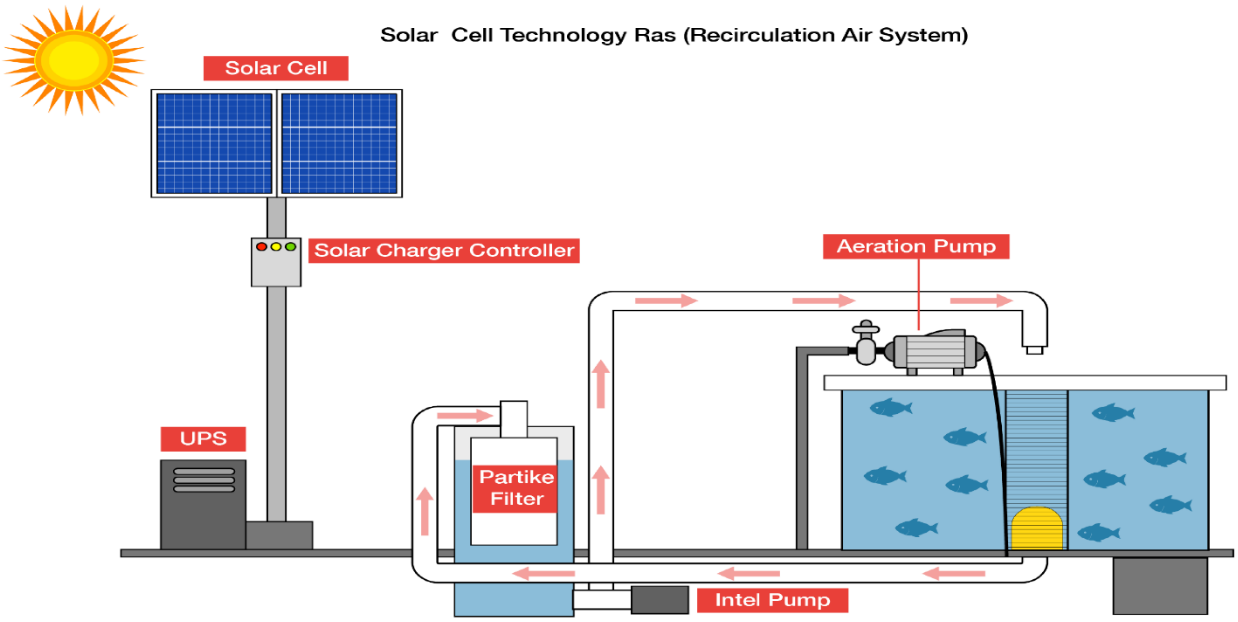

Figure 7: The solar cell recirculated aquaculture system.
Source: Vo *et al*., 2021

6.3 Solar Dryers and Biogas Utilization

Additional renewable solutions improve hatchery sustainability and waste management:

a) Solar dryers are used to process live-feed cultures, microalgae, and hatchery equipment, reducing microbial contamination and energy use.

b) Bio - Gas systems convert organic waste (sludge, biofloc residues) into renewable energy for heating tanks or powering ancillary operations.

These systems close nutrient and energy loops, contributing to circular economy principles and reducing greenhouse gas emissions associated with conventional energy and waste disposal methods (Chen *et al*., 2025; Cozzolino *et al*., 2025).

Integrating renewable energy and low-carbon technologies into hatchery operations supports both climate adaptation and mitigation (Figure 8). Solar-powered systems, low-energy RAS, biogas utilization, and solar dryers reduce greenhouse gas emissions while providing operational resilience under climate variability.

Figure 8: Structure of a renewable energy fish farming at a farm in Egypt
Source: Baioumi *et al*. 2024.

These technologies, when combined with breeding, larval rearing, and disease control innovations, create a holistic, climate-smart hatchery system capable of maintaining productivity, efficiency, and environmental stewardship in the face of accelerating climate change.

7.0 Sustainability and Environmental Considerations

Climate-smart hatcheries are not only designed to enhance resilience and productivity but also to minimize environmental impacts and promote long-term ecological sustainability. The integration of efficient resource management, waste reduction, environmental monitoring, and ecosystem-based planning (Figure 9) ensures that hatchery operations contribute positively to surrounding aquatic ecosystems while reducing their carbon footprint (Eze *et al*., 2021; Chen *et al*., 2023; Yusoff *et al*., 2024).

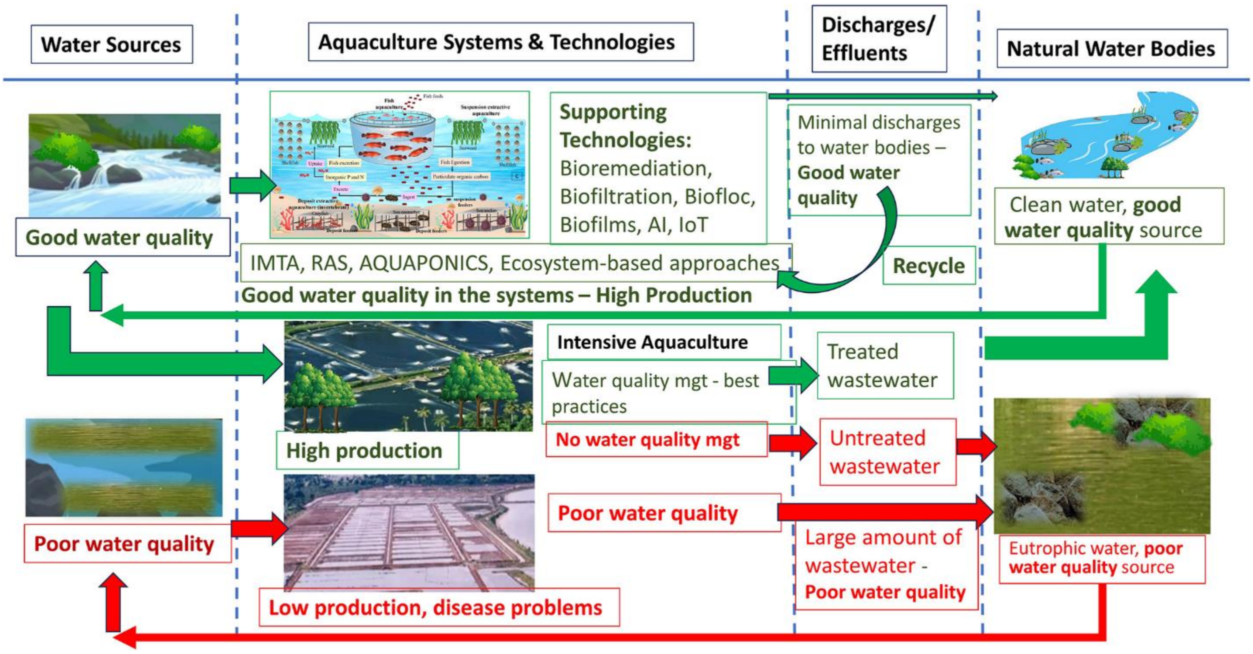

Figure 9: Smart and Sustainable Aquaculture
Source: Yusoff *et al*., 2024

7.1 Efficient Water Use

Water scarcity is a growing challenge in many aquaculture regions, exacerbated by climate change. Climate-smart hatcheries adopt:

i. Recirculating aquaculture systems (RAS) and biofloc-based larval rearing to minimize water withdrawal.

ii. Precision water management using sensors and automated systems to monitor and adjust flow rates based on real-time demand.

iii. Water reuse and treatment strategies to recycle effluents, reducing freshwater extraction and nutrient loading into natural water bodies.

These approaches conserve water, maintain high water quality, and reduce the vulnerability of hatcheries to climate-induced droughts or seasonal variability.

7.2 Waste Reduction and Nutrient Management

Hatchery effluents can introduce organic matter, nitrogen, and phosphorus into surrounding ecosystems, contributing to eutrophication. Climate-smart practices include:

i. Conversion of sludge and biofloc residues into biogas or fertilizer.

ii. Use of integrated multi-trophic aquaculture (IMTA) systems, where waste from hatcheries supports growth of algae or filter-feeding species.

iii. Optimized feeding regimes to minimize feed waste and nutrient excretion.

These measures reduce environmental pollution, promote circular resource use, and enhance hatchery sustainability.

7.3 Environmental Monitoring

Ongoing monitoring is critical for both hatchery performance and ecosystem health:

i. Sensors and IoT platforms track water quality parameters such as pH, dissolved oxygen, ammonia, temperature, and turbidity.

ii. Remote sensing and GIS can be applied for site selection, habitat protection, and early warning of harmful algal blooms or climate anomalies.

iii. Data-driven decision-making allows hatchery managers to adjust operations proactively, mitigating environmental impacts and improving larval survival.

Such monitoring ensures that hatcheries operate sustainably and respond dynamically to both internal and external environmental stressors.

7.4 Ecosystem-Based Hatchery Siting

Hatchery location significantly affects both productivity and environmental sustainability:

i. Sites are selected based on water availability, quality, and natural buffering capacity to withstand climate extremes.

ii. Ecosystem-based planning integrates hatcheries with surrounding wetlands, mangroves, or estuarine habitats to provide natural filtration, biodiversity support, and climate resilience.

iii. Proximity to natural water flows and safe discharge zones minimizes ecological disruption while enhancing hatchery stability under extreme weather events.

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Sustainability and environmental stewardship are integral to climate-smart hatcheries. By conserving water, reducing waste, monitoring environmental conditions, and adopting ecosystem-based siting, hatcheries minimize their ecological footprint while enhancing resilience to climate variability. These practices complement innovations in breeding, larval rearing, disease control, and renewable energy integration, forming a holistic framework for sustainable and climate-resilient aquaculture.

8.0 Conclusion

Climate - Smart hatchery management offers a comprehensive and transformative framework for enhancing aquaculture resilience under a rapidly changing climate. By addressing stage-specific vulnerabilities such as thermal stress, hypoxia, acidification, and pathogen exposure through innovations in breeding, larval rearing, disease control, and operational management, hatcheries can maintain high-quality, robust seed production. Adaptive breeding strategies, including selective breeding, temperature-adaptive broodstock selection, genomic selection, and gene editing, enable the development of heat-, salinity-, and disease-tolerant strains. Complementary interventions in larval rearing precision environmental control, biofloc and green water systems, microbiome modulation, and optimized nutrition enhance survival, growth, and stress resilience.

Integrated disease management, combining vaccination, immunostimulants, early digital diagnostics, and biosecurity, mitigates climate-driven pathogen risks, while renewable energy adoption and low-carbon operational strategies reduce environmental footprints and operational costs. Efficient water use, nutrient recycling, environmental monitoring, and ecosystem-based hatchery siting further strengthen ecological sustainability.

Collectively, these approaches create a holistic, climate-smart hatchery model that is technologically advanced, environmentally responsible, and resilient to climate variability. Implementing these strategies at scale will be essential to secure sustainable aquaculture production, safeguard food security, and support livelihoods in regions increasingly affected by climate change.

References

Abalasei, M. E., Toma, D., Dorus, M. & Teodosiu, C. (2025). The Impact of Climate Change on Water Quality: A Critical Analysis. *Water*, *17*(21), 3108. https://doi.org/10.3390/w17213108

African Development Bank (AFB) (2022). The Potential of Green Aquaculture in Africa: Status and Prospects for Seaweed Farming. 19 April 2022. https://www.afdb.org/en/documents/potential-green-aquaculture-africa-status-and- prospects-seaweed-farming

Ajayi, O. M., Oyen, K. J., Davies, B., Finch, G., Piller, B. D., Harmeyer, A. A., Wendeln, K., Perretta, C., Rosendale, A. J, & Benoit, J. B. (2024). Egg hatching success is influenced by the time of thermal stress in four hard tick species. *J Med Entomol*. 61(1):110-120. doi: 10.1093/jme/tjad142.

Akande, B. H. & Oyarekhua, O. S. (2025). Simplified climate change adaptation strategies for livestock development in low-and middle-income countries. *Frontiers in Sustainable Food Systems*, *9*. DOI=10.3389/fsufs.2025.1566194

Akinjogunla, V. F. & Usman, B. I. (2023). Biochemical compositions in the carcasses of some indigenous finfishes in Ajiwa Irrigation Dam, Katsina State, Northern Nigeria. *Acta Natura Et Scientia* 4 (2): 216-224.

Benjamin, E. O., Ola, O., & Buchenrieder, G. R. (2022). Feasibility Study of a Small-Scale Recirculating Aquaculture System for Sustainable (Peri-)Urban Farming in Sub-Saharan Africa: A Nigerian Perspective. *Land*, *11*(11), 2063. https://doi.org/10.3390/land11112063

Bohnes, F. A., Hauschild, M. Z. W., Schlundt, J., Nielsen, M. & Laurent, A. (2022). Environmental sustainability of future aquaculture production: Analysis of Singaporean and Norwegian policies, *Aquaculture*, 549, 737717, https://doi.org/10.1016/j.aquaculture.2021.737717

Brenckman, C. M., Parameswarappa Jayalakshmamma, M., Pennock, W. H., Ashraf, F., & Borgaonkar, A. D. (2025). A Review of Harmful Algal Blooms: Causes, Effects, Monitoring, and Prevention Methods. *Water*, *17*(13), 1980. https://doi.org/10.3390/w17131980

Canosa, L. F. & Bertucci, J. I. (2023). The effect of environmental stressors on growth in fish and its endocrine control. *Front Endocrinol (Lausanne)*, 14:1109461. doi: 10.3389/fendo.2023.1109461.

Carlino-Costa, C., & Belo, M. A. d. A. (2025). Ensuring Fish Safety Through Sustainable Aquaculture Practices. *Hygiene*, *5*(4), 51. https://doi.org/10.3390/hygiene5040051

Chapra, S. C., Camacho, L. A., & McBride, G. B. (2021). Impact of Global Warming on Dissolved Oxygen and BOD Assimilative Capacity of the World’s Rivers: Modeling Analysis. *Water*, *13*(17), 2408. https://doi.org/10.3390/w13172408

Chen, H., Zhao, G., & Ramzan, M. (2025). The Path to Environmental Sustainability: How Circular Economy, Natural Capital, and Structural Economic Changes Shape Greenhouse Gas Emissions in Germany. *Sustainability*, *17*(13), 5982. https://doi.org/10.3390/su17135982

Chen, P, Kim, H. J., Thatcher, L. R., Hamilton, J. M., Alva, M. L., Zhou (George), Z. & Brown, P. B. (2023) Maximizing nutrient recovery from aquaponics wastewater with autotrophic or heterotrophic management strategies. *Bioresource Technology Reports* 21, 101360. https://doi.org/10.1016/j.biteb.2023.101360

Combe, M., Reverter, M., Caruso, D., Pepey, E., & Gozlan, R. E. (2023). Impact of Global Warming on the Severity of Viral Diseases: A Potentially Alarming Threat to Sustainable Aquaculture Worldwide. *Microorganisms*, *11*(4), 1049. https://doi.org/10.3390/microorganisms11041049

Cortes, J. R., Benitez, I. B., Bernajocele Jalyn S. Baldoza, Charm Angel R. Pardillo, Kathleen Mae A. Auxtero, Kristina P. Badec, Daryl Anne B. Varela (2026). Climate-smart aquaculture: Innovations and challenges in mitigating climate change impacts on fisheries and coastal agriculture, *Aquaculture and Fisheries*, 11 (2), 221-231, https://doi.org/10.1016/j.aaf.2025.08.009

Cozzolino, M., Salomone, R., Ricca, B. & Gulotta, T. M. (2025). Circular economy in aquaculture: An Italian survey to understand perceptions, challenges and options for transition, Marine Policy, 176,106660, https://doi.org/10.1016/j.marpol.2025.106660

Dai, L., Chen, Y. & Li, C. (2025). Environmental factor impacts on behavioral and physiological responses of aquaculture species in recirculating aquaculture systems: Mechanisms and regulation, *Aquaculture Reports*, 44, 103036, https://doi.org/10.1016/j.aqrep.2025.103036.

Dildar, T., Cui, W., Ikhwanuddin, M. & Ma, H. (2025). Aquatic Organisms in Response to Salinity Stress: Ecological Impacts, Adaptive Mechanisms, and Resilience Strategies. *Biology* (*Basel*), 14(6):667. doi: 10.3390/biology14060667.

Edwards, T. M., Puglis, H. J., Kent, D. B., Durán, J. L., Bradshaw, L. M. & Farag, A. M. (2024). Ammonia and aquatic ecosystems – A review of global sources, biogeochemical cycling, and effects on fish, *Science of The Total Environment*, 907, 167911, https://doi.org/10.1016/j.scitotenv.2023.167911.

Elgendy, M.Y., Ali, S.E., Dayem, A.A. Khalil, R. A, Moustafa, M. M. & Abdelsalam, M (2024). Alternative therapies recently applied in controlling farmed fish diseases: mechanisms, challenges, and prospects. *Aquacult Int* **32**, 9017–9078 (2024). https://doi.org/10.1007/s10499-024-01603-3

Eze, E, Halse, S & Ajmal, T. (2021) Developing a novel water quality prediction model for a South African aquaculture farm. *Water* 13, 1782. https://doi.org/10.3390/w13131782

FAO. 2024. The State of World Fisheries and Aquaculture 2024. Blue Transformation in action. Rome.https://doi.org/10.4060/cd0683en

Ghorbanzadeh, Z., Panahi, B., Purhang, L., Hossein Panahi, Z., Zeinalabedini, M., Mardi, M., Hamid, R., & Ghaffari, M. R. (2025). Integrative Genomics and Precision Breeding for Stress-Resilient Cotton: Recent Advances and Prospects. *Agronomy*, *15*(10), 2393. https://doi.org/10.3390/agronomy15102393.

Gupta, S., Makridis, P., Henry, I., Velle-George, M., Ribicic, D., Bhatnagar, A., Skalska-Tuomi, K., Daneshvar, E., Ciani, E., Persson, D. & Netzer, R. (2024). Recent Developments in Recirculating

Aquaculture Systems: A Review, *Aquaculture Research*, 2024, 6096671, 21 pages, 2024. https://doi.org/10.1155/are/6096671

Haque, M. M., Mahmud, M. N., Ahammad, A. K. S., Alam, M. M., Bablee, A. L., Hasan, N. A., Bashar, A., & Hasan, M. M. (2025). Building Climate Resilient Fisheries and Aquaculture in Bangladesh: A Review of Impacts and Adaptation Strategies. *Climate*, *13*(10), 209. https://doi.org/10.3390/cli13100209

Jeyachandran, S. (2025). Review on climate change, microbial resilience, and disease risks in global aquaculture systems. *Comp Immunol Rep*. 9:200240. doi: 10.1016/j.cirep.2025.200240.

Kari, Z. A. (2025). Abiotic and biotic factors affecting the immune system of aquatic species: A review, *Comparative Immunology Reports*, 9, 200230, https://doi.org/10.1016/j.cirep.2025.200230.

Karimanzira, D. (2025). Comprehensive Fish Feeding Management in Pond Aquaculture Based on Fish Feeding Behavior Analysis Using a Vision Language Model. *Aquaculture Journal*, *5*(3), 15. https://doi.org/10.3390/aquacj5030015

Lema, S. C., Luckenbach, J. A., Yamamoto, Y. & Housh, M. J. (2024). Fish reproduction in a warming world: vulnerable points in hormone regulation from sex determination to spawning. *Philos Trans R Soc Lond B Biol Sci*.;379(1898):20220516. doi: 10.1098/rstb.2022.0516.

Maulu, S., Hasimuna, O. J., Haambiya, L. H., Monde, C., Musuka C. G., Makorwa, T. H., Munganga, B. P., Phiri K. J. & Nsekanabo, J. D. (2021). Climate Change Effects on Aquaculture Production: Sustainability Implications, Mitigation, and Adaptations. Frontiers in Sustainable Food Systems. 5 DOI=10.3389/fsufs.2021.609097

Mbaka, M., Cox, J.H. & Ronan, S. 2022. Aquaculture in Africa: Aquatic animal welfare, impact on the environment, and the sustainability of the sector. Available from the Wellbeing International Studies Repository at: https://www.wellbeingintlstudiesrepository.org/aw_farm_aqua/1

Mitra, A. (2023). Climate change and reproductive biocomplexity in fishes: Management approaches for fisheries and aquaculture. https://www.globalseafood.org/advocate/climate-change-and-reproductive-biocomplexity-in-fishes-management-approaches-for-fisheries-and-aquaculture/

Mitra, A., Abdel-Gawad, F. K., Bassem, S., Barua, P., Assisi, L., Parisi, C., Temraz, T. A., Vangone, R., Kajbaf, K., Kumar, V., & Guerriero, G. (2023). Climate Change and Reproductive Biocomplexity in Fishes: Innovative Management Approaches towards Sustainability of Fisheries and Aquaculture. *Water*, *15*(4), 725. https://doi.org/10.3390/w15040725

Mwakapoma, S., Lyimo, R. & Kichonge, B. (2025). Sustainable hydropower planning and climate resilience in Tanzania for East African Power Pool (EAPP) energy security. *Discov Energy* **5**, 43 (2025). https://doi.org/10.1007/s43937-025-00105-4

Nayak, A., Maity, T., Molla, M.H., & Das, K.S. (2025). Climate-Resilient Aquaculture: Strategies for Sustainable Future. In: Singh, A.K., Kumar, P., Singh, S.S. (eds) Sustainable Agriculture Management in Semi-Arid Climates. pp 405–425. Springer, Cham. https://doi.org/10.1007/978-3-031-94066-8_17

OECD/FAO (2025), *OECD-FAO Agricultural Outlook 2025-2034*, OECD Publishing, Paris/FAO, Rome, https://doi.org/10.1787/601276cd-en.

Okon, E. M., Birikorang, H. N., Munir, M. B., Kari, Z. A., Téllez-Isaías, G., Khalifa, N. E., Abdelnour, S. A., Eissa, M. E. H., Al-Farga, A., Dighiesh, H. S., & Eissa, E.-S. H. (2023). A Global Analysis of Climate Change and the Impacts on Oyster Diseases. *Sustainability*, *15*(17), 12775. https://doi.org/10.3390/su151712775

Padeniya, U., Davis, D. A., Wells, D. E., & Bruce, T. J. (2022). Microbial Interactions, Growth, and Health of Aquatic Species in Biofloc Systems. *Water*, *14*(24), 4019. https://doi.org/10.3390/w14244019

Prasad, R. D., Chand, D. A., Lata, S. S. S. L. & Kumar, R. S. (2025). Beyond Energy Access: How Renewable Energy Fosters Resilience in Island Communities. *Resources*, *14*(2), 20. https://doi.org/10.3390/resources14020020

Saeed, S., Makhdum, M. S. A., Anwar, S., & Yaseen, M. R. (2023). Climate Change Vulnerability, Adaptation, and Feedback Hypothesis: A Comparison of Lower-Middle, Upper-Middle, and High-Income Countries. *Sustainability*, *15*(5), 4145. https://doi.org/10.3390/su15054145

Samy-Kamal, M. (2025). The Human Cost of Seafood: Impacts of Global Trade and Aquaculture Expansion. *Sustainability*, *17*(18), 8504. https://doi.org/10.3390/su17188504

Scanes, E., Siboni, N., Brandimarti, M. & Seymour, J. (2025). Intertidal Warming Causes Mortality and Disrupts the Microbiome of Oysters. *Environ Microbiol*. 27(7):e70152. doi: 10.1111/1462-2920.70152.

Siddique, M. A. B., Mahalder, B., Haque, M. M., Bashar, A., Hasan, M. M., Shohan, M. H., Talukdar, M. M. N., Biswas, J. C., & Ahammad, A. K. S. (2023). Assessment of Embryonic and Larval Development of Nile Tilapia under the Traditional and Re-Circulatory Thermostatic System in Relation to Climatic and Water Quality Variations. *Aquaculture Journal*, *3*(2), 70-89. https://doi.org/10.3390/aquacj3020008

Simasiku, E. K., Hove, K., Kanyeme, M. N., Awala, S. K., Matengu, K. K., & Iita, T. I. (2024). Comparative Effect of Fish Feeds on the Initial Growth and Survival Rate of Juvenile Redbreast Tilapia (*Coptodon rendalli*) under Early Hatchery Conditions. *Aquaculture Journal*, *4*(3), 180-191. https://doi.org/10.3390/aquacj4030013

The Edge, Malasyia (2025). https://theedgemalaysia.com/article/startup-engineer-iot-entrepreneur

Torsabo, D., Ishak, S. D., Noordin, N. M., Waiho, K., Koh, I. C. C., Yazed, M. A. & Abol-Munafi, A. B. (2024). Optimizing reproductive performance in pangasius catfish broodstock: A review of dietary and molecular strategies, *Veterinary and Animal Science*, 25,100375, https://doi.org/10.1016/j.vas.2024.100375.

Vo, T. T. E., Ko, H., Huh, J.-H., & Park, N. (2021). Overview of Solar Energy for Aquaculture: The Potential and Future Trends. *Energies*, *14*(21), 6923. https://doi.org/10.3390/en14216923

Wright-Fairbanks, E. K., Munroe, D. M., Hunter, E. J., Wilkin, J. & Saba, G.K., (2025). Meta-analysis of larval bivalve growth in response to ocean acidification and its application to sea Scallop larval dispersal in the mid-Atlantic bight. *Estuaries and Coasts*, 48(2), pp. 1-18. https://doi.org/10.1007/s12237-024-01469-x.

Xu P, Wu F, Yan Q, Ao B, Wang S, Chen L, Wang L, & Zhang J. (2025). Hybridization Drives Trait Integration in Telomere-To-Telomere Apocynum Genomes. *Plant Biotechnol J*. (11):5129-5145. doi: 10.1111/pbi.70288.

Yan, J., Zhang, F., Liang, F., Zhao, C., Yin, S. & Zhang, G. (2025). Effects of Hypoxia and Reoxygenation on Hypoxia-Responsive Genes, Physiological and Biochemical Indices in Hybrid Catfish (*Pelteobagrus vachelli* ♀ × *Leiocassis longirostris* ♂). *Biology (Basel*). 23;14(8):915. doi: 10.3390/biology14080915.

Yusoff, F. M, Umi, W. A. D., Ramli, N. M. & Harun, R. (2024). Water quality management in aquaculture. *Cambridge Prisms: Water*. 2: e8. doi:10.1017/wat.2024.6.

Zhu, Z, Song, Z., Xu, S., Wang, S., Chen, X., Wang, Y., & Zhu, Z. (2024). The development of fishery-photovoltaic complementary industry and the studies on its environmental, ecological and economic effects in China: A review, *Energy Nexus*, 15, 100316, https://doi.org/10.1016/j.nexus.2024.100316.