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Chapter 2

Climate Smart Aquaculture: Best Practices and Innovations

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Abstract

Aquaculture facilitates food security in the changing climate through its best innovative technologies, which provide protein-rich aquatic nutrition, livelihood opportunities and ecosystem sustainability through integrated aquaculture systems. Anthropogenic activity causes greenhouse gas emissions. Technological breakthroughs in aquaculture are necessary to combat the threat of climate change. Climate-SMART Aquaculture is a revolutionary approach anticipated to enhance global food security and environmental sustainability in contempt of climate change. Its adaptation and mitigation strategies promote increased climate resilience and adaptive ability to climate change. The key components of climate smart aquaculture include sustainable development practices, developing climate resilient species and innovative technologies such as RAS, IMTA and AI monitoring of aqua-farm. The Climate-SMART Aquaculture emphasizes three primary objectives such as long-term increases in production along with revenue, climate change adoption and climate change mitigation. This chapter explains how climate-smart aquaculture helps in mitigating climate-change impacts through innovative aquaculture practices.

Keywords Aquaculture, Climate change, Climate-Smart Aquaculture (CSA), Greenhouse gases, Recirculatory Aquaculture System (RAS)

1. Introduction

Climate-smart aquaculture endeavours to practices that improve national food security and development objectives while reducing or eliminating greenhouse gas emissions, boosting resilience (adaptation) and sustainably increasing productivity. It requires streamlining natural resource use for efficient fish and seafood production and safeguarding aquatic ecosystems through enhancing community adaptation and climate resilience by

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identifying effective strategies to mitigate vulnerability. The aquaculture and fisheries sectors are projected to encounter significant implications on production and livelihoods due to change in climate and variability, which influence the distribution of resources. A variety of direct and indirect consequences on fisheries and aquaculture are expected. Aquatic foods are crucial for tackling climate change. In accordance with United Nations Framework Convention on Climate Change (UNFCCC), policies have recently focused on the correlation between food production, aquatic ecosystems and climate change. The UNFCCC Ocean Dialogue of 2023 acknowledged the necessity of incorporating aquatic foods into national and international climate action-related processes, given their considerable potential to provide vital climate solutions (FAO, 2024).

2. Implications of Climate Change on Aquaculture and Fisheries

The well-being of an ecosystem is connected to a fishery's output, which supplies nourishment, shelter and even the dispersal of seeds. Climate change is a significant issue, with a projected rise in average global temperatures. Climate change influences its states in terms of attribute variation and permanence over long periods of time, typically decades or more (IPCC, 2007). Climate change can affect aquaculture productivity by means of rising sea levels and temperatures, Monsoon rainfall patterns, extreme weather and water-related stress (Ficke *et al.*, 2007; Adhikari *et al.*, 2018). Global warming could have the impact of raising the water temperatures in some habitats to suboptimal or fatal levels for resident fishes that have restricted dispersion capacity or for fishes living in systems that inhibit migration. Critical Thermal Maxima (CT_{Max}) and Critical Thermal Minima (CT_{Min}) define the top and lower ends of each fish's thermal range (Becker and Genoway, 1979).

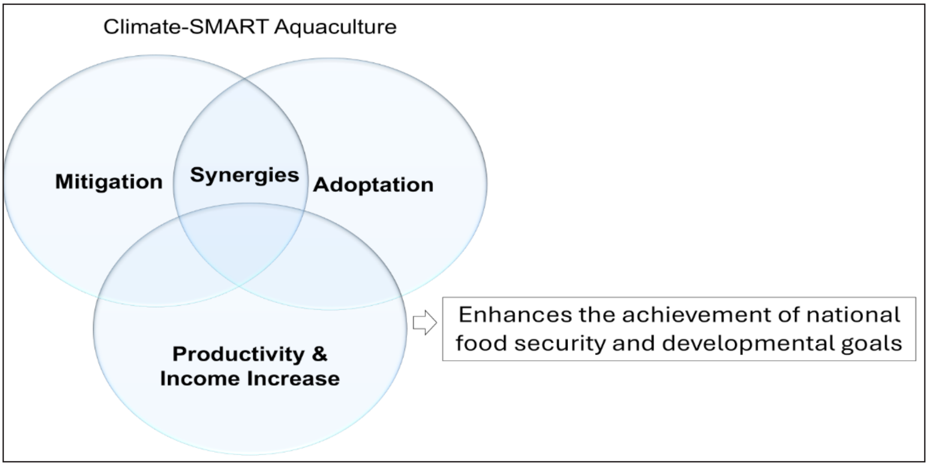

Figure 1: Climate-smart aquaculture and its components (Source: FAO, 2013)

According to reports, climate change has an enormous impact on aquaculture and its sustainability, productivity and profitability; physical impacts such as ocean acidification lead to a decrease in ocean water pH by 0.3 to 0.5 units (Kunkel *et al.*, 2022). Occurrence of extreme weather events with high severity, rise in sea level followed by coastal erosion and many more impacts.

Biologically alters the distribution of plankton and zooplankton communities, results in changes in fish availability, migratory and distribution patterns and impacts broodstock and larval development; promotes parasite proliferation and disease prevalence. Socioeconomic consequences include decreased aquaculture productivity and revenue, increased feed costs and competition for resources, as well as implications on fishermen's food security and livelihoods, which lead to community displacement.

3. The Scope of Aquaculture in Climate-Smart Food Production

The aquaculture enterprises are expected to increase at an average yearly pace of 7.97% between 2024 and 2032. Government programs to assist sustainable aquaculture, technological advances in farming methods and rising demand for protein-rich meals are among the factors driving this rise. Aquaculture accounts for more than 56% of total fish output worldwide, with farm-raised fish accounting for more than 57% of global fish consumption. Aquaculture is one of the most unique farming methods for achieving food security in the midst of climate change (Obiero *et al.*, 2021). In addition, it provides co-benefits for better livelihoods, nutrition and environmental sustainability by integrating crop-livestock systems.

In 2022, the global aquaculture production was 114 million tons. Asia dominates aquaculture output, accounting for 90% of the worldwide total. China, Indonesia, India, Vietnam and Thailand are the top five aquaculture producers (FAO, 2024). However, aquaculture offers a variety of environmental issues that differ depending on the production system and may cause a significant environmental impact. It can cause considerable ecological footprints, particularly for intensive culture systems (Munguti *et al.*, 2022).

According to Munguti *et al.* (2022), the goal of aquaculture research is to create and validate climate-smart aquaculture (CSA) technologies, innovations and management practices (TIMPs) for sustainable aquaculture. As a result of land and water constraints, resource scarcity and competition from other users, to achieve sustainable intensification of aquaculture, the model fish farms with technologically inventive aquaculture systems such as tank-based systems, hydroponic systems, aquaponics cultivation, Integrated Multi-Trophic Aquaculture (IMTA) and recirculating aquaculture systems (RAS),Renewable energy integration (*e.g.*, solar, wind), Offshore aquaculture, Biofloc technology, Climate-resilient species selection, Genetic enhancement for climate tolerance Genetic improvement for climatic resistance, including increased density and high capacity for carrying intense cultivation in cages in reservoirs and lakes, as well as adaptive management and monitoring using GPS, GIS software systems and artificial intelligence.

4. Green House Gas Emissions from Aquaculture

Greenhouse gases are gaseous elements in the atmosphere, that are both man-made and natural, which absorb and emit radiation at certain wavelengths in the infrared range emitted by the Earth's surface, atmosphere and clouds. This characteristic causes the greenhouse effect. The primary greenhouse gases in the Earth's atmosphere are carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). The Montreal Protocol deals with a number of wholly human-caused greenhouse gases that exist in the environment, such as hydrocarbons and other chlorine and bromine-containing substances. Along with CO_2, CH_4 and N_2O, the Protocol of Kyoto covers the greenhouse gases SF_6, HFCs and PFCs (IPCC, 2018). Climate change, particularly greenhouse gas (GHG) emissions from food distribution chains, is a serious environmental and societal concern. To foster the long-term growth of aquaculture, we must first acknowledge its influence on worldwide emissions of greenhouse gases and how to reduce them. MacLeod *et al.* (2020) estimated the GHG emissions associated with the culture of the primary aquatic species raised for human food, namely finfish (Indian major carps, catfish, cyprinids, salmonids and tilapias), shrimps/prawns and bivalves. This approach determines the primary GHG emissions from "cradle to farm-gate" for the following aquaculture operations,

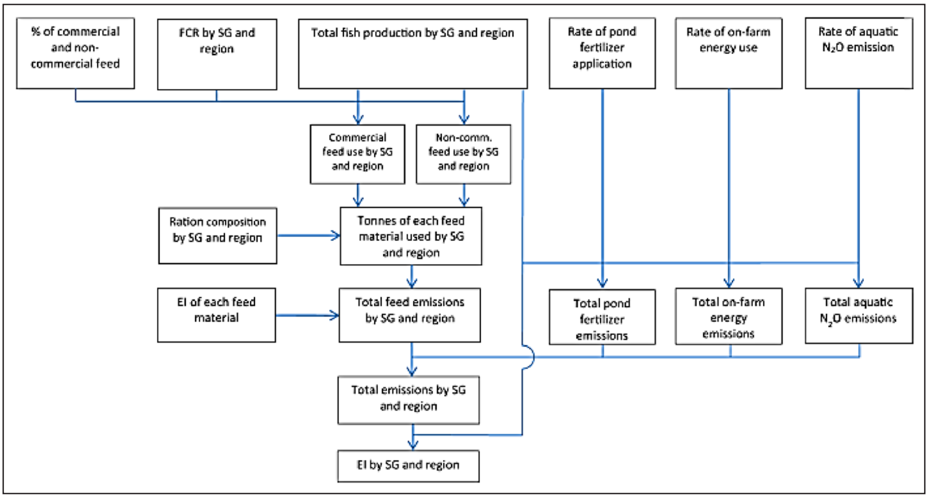

Figure 2: A schematic illustration of the approach used to assess total emissions and emissions intensity [SG species-group; FCR feed conversion ratio; EI emissions intensity] (Source: MacLeod *et al.*, 2020)

including emissions intensity (*i.e.*, kg of GHG emissions per unit of edible production) of aquaculture.

5. GHG Emissions Sources

5.1. Methane (CH_4)

Methane (CH_4) is a key greenhouse gas (GHG) that absorbs radiation, influences atmospheric temperature and weather and contributes to climate change. It is produced under anaerobic conditions in the pond sediments, primarily from the decomposition of organic matter. Excessive organic matter concentration from uneaten feed, faeces and decomposing algae can promote methane generation, particularly in ponds with limited oxygenation.

5.2. Nitrous Oxide (N_2O)

Nitrification and denitrification processes in the pond contribute to the nitrous oxide emissions. Excess nitrogen from feed or fertilizers promotes these processes. Poorly managed nutrient inputs can exacerbate nitrous oxide emissions.

In accordance with Hu *et al.* (2012), microbial nitrification and denitrification, like in terrestrial or other aquatic ecosystems, are responsible for N_2O emissions from the fish farm's water bodies. However, the emissions from the pond surface to the air depend on pH of the pond and dissolved oxygen level, both of which vary significantly, measuring them is difficult.

5.3. Carbon Dioxide (CO_2)

Respiration by aquatic organisms' releases CO_2, including fish and microorganisms and the degradation of organic material. Although ponds can also absorb CO_2 *via* photosynthesis, intensive farming can result in net emissions.

6. Key Components of Climate-Smart Aquaculture

i) Climate Resilience: Climate-resilient species attributes to the resilience in aquaculture. By developing disease resistant species and adopting management practices.

ii) Sustainable Intensification: The practice of increasing aquaculture productivity without negatively impacting the environment. This can be achieved through the optimized water use and adoption of efficient feeding practices.

iii) Carbon Sequestration: Aquaculture systems involving seaweed farming and shellfish farming acts as carbon sinks and facilitates nutrient cycling and contributes to GHG reduction.

iv) Technological Innovations: Technological enhancements such as sensor-based monitoring systems, precision aquaculture, satellite and drone technology for monitoring water quality parameters and biotechnological innovations are essential tools for implementing climate-smart aquaculture.

7. Climate-Smart Aquaculture Technologies

Climate-smart aquaculture technology, advancements and management techniques are critical in developing resilient, sustainable and productive aquaculture systems in the context of climate change.

7.1. Recirculating Aquaculture Systems (RAS)

The Recirculatory Aquaculture System (RAS) is a system that utilizes and recycles water following mechanical and biological filtration eliminates suspended particles and metabolites. This approach is utilized for high-density fish production with minimal land and water requirements. RAS may be climate-smart by managing environmental factors such as oxygen, water quality and temperature, allowing species to be farmed under controlled circumstances and reducing the effects of climatic fluctuation.

7.2. Precision Aquaculture

Precision aquaculture employs a range of sensors to acquire information into the farm environment and make choices that enhance fish health, development and monetary return and decrease environmental risk. This tendency is similar to improvements in agriculture, where sensors and other observation technology improve understanding of crop health and animal welfare (O'donncha *et al.*, 2019).

7.3. Integrated Multi-Trophic Aquaculture (IMTA)

A sustainable and cutting-edge aquaculture technique called Integrated Multi-Trophic Aquaculture (IMTA) grows different types of seafood in the same aquatic habitat. By employing one species' waste products as nutrition for another, IMTA aims to improve system efficiency and create a closed-loop system that reduces waste and boosts productivity. The farmed species serve as biofilters, with each level having its own separate commercial value, ensuring both economic and environmental sustainability (Antonucci and Costa, 2020).

8. Climate-Smart Aquaculture Innovations

8.1. Low-Carbon Energy Solutions

The integration of renewable energy sources in aquaculture farming systems, such as wind or solar power, helps to minimize greenhouse gas emissions and carbon footprints connected with farm activities.

8.2. Selective Breeding and Genetic Improvement

Selective breeding and genetic improvement are crucial for enhancing the aquaculture productivity. These innovations focus majorly on resilient aquaculture species to climate change stressors and disease outbreaks.

8.3. Alternative and Sustainable Feeds

The reduced reliance on wild-caught fishmeal and fish oil is another important aspect of climate-smart aquaculture. Insect meal, plant-based proteins and algae-based feed ingredients offer sustainable feed alternatives that reduce reliability on marine resources. The efficient feed formulation is crucial in achieving increased growth rates and reduces waste.

9. Conclusion

To ensure the sustainability and resilience of the aquaculture sector in facing global climatic conditions there is a need for climate smartness of aquaculture management practices, technologies and innovations. By incorporating advanced technologies, adopting precision culture practices, developing resilient species, integrating sustainable management practices and improving resource efficiency one can successfully practice climate-SMART aquaculture, which can play a significant role in adapting to the climate change realities. It creates a smart pathway for sustainable aquaculture to thrive as a climate-smart and climate-resilient food production system.

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