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The Future of Aquaculture: Sustainable Development, Economic Growth, and Environmental Protection

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Abstract Aquaculture is one of the fastest-growing food production sectors globally, playing a vital role in food security, employment, and economic development. This review synthesizes literature spanning from 1988 to 2024, with a primary focus on contemporary advancements and policy shifts within the last decade, to evaluate the balance between seafood demand and ecosystem integrity. While it supports millions of livelihoods, ensuring sustainability remains a challenge. The study identifies that traditional intensive systems have caused groundwater salinization, mangrove loss, and chemical residue accumulation. Modern aquaculture utilizes diverse species-seaweeds, mollusks, and finfish to promote resource optimization. With the decline in capture fisheries, many nations have shifted toward inland and integrated farming systems. Sustainable development now emphasizes ecosystem-based management, including wetland conservation, effective effluent treatment, and biodiversity protection. Strengthening biosecurity, disease surveillance, and reduced antibiotic use are essential for meeting global hygiene standards. In tropical regions, integrated models like rice-fish culture are evolving into advanced systems such as Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), and Biofloc Technology (BFT). These innovations aim to minimize footprints while improving resource efficiency and biological balance. Overall, promoting environmentally responsible and socially inclusive aquaculture is crucial for conserving marine ecosystems and safeguarding the future of global seafood security.

Keywords Sustainable aquaculture; Integrated farming; IMTA and livestock farming; Organic aquaculture

1 Introduction

Aquaculture plays a vital role in ensuring global food security and enhancing the livelihoods of small-scale and marginal fish farmers. Currently, the oceans cover approximately 70% of the Earth's surface, hosting biological communities ranging from microscopic prokaryotes to the mammoth blue whale. These marine ecosystems provide essential services and food products; however, they are increasingly threatened by ocean acidification, rising sea surface temperatures, marine litter, and coastal pollution. Furthermore, these ecosystems remain relatively under-explored, offering significant potential for the discovery of novel bioactive molecules and secondary metabolites.

The fisheries sector is multifaceted, encompassing capture, commercial, artisanal, and recreational fishing, alongside freshwater and marine aquaculture. Notably, aquaculture has overtaken capture fisheries as the primary source of seafood for human consumption, serving as a vital alternative to mitigate food security challenges and prevent the depletion of wild fish stocks (White and Lopez, 2017). Global production has escalated from 19 million tons in 1950 to 122 million tons in 2020 (FAO, 2022a). Sustainable management is essential to strengthen the resilience of coastal ecosystems and achieve the United Nations Sustainable Development Goal (SDG-14), which emphasizes the conservation and equitable use of oceanic resources by 2030.

Developing sustainable "incubator systems" in maritime nations can foster environmentally conscious businesses and ensure equitable economic growth (OECD/World Bank, 2016). However, the scientific community recognizes that the intensive use of land and water, chemical eco toxicity, and the introduction of non-native species are