

The Role of Aquaculture in Enhancing Global Fish Production and Aquatic Biodiversity

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Abstract: Aquaculture, which contributes the major portion to fish production at the global level, has helped to narrow the gap between capture fishery output and the increasing demand for protein sources worldwide. In this study, aquaculture production and biodiversity changes across ecological zones are assessed simultaneously with their contribution to increasing the global fish production potential. Global production data of different species from different regions, species diversity indices, and environment management effectiveness are compiled for different aquaculture systems, including recirculating aquaculture systems (RAS), pond systems, integrated rice-fish culture, and mariculture in Asia-Pacific, Europe, America, and Africa in this comparative and integrative assessment. Data showed that the aquaculture output was 94.3 million metric tons at a global scale by 2023, and its share in Asia-Pacific was more than 83% of the total output. The results for different species indicated that mollusk and seaweed culture systems had the highest compatibility with aquatic biodiversity (indices, 0.81-0.90), whereas intensive culture for crustaceans was the least compatible with diversity (0.58). Statistical data proved a significant correlation between sustainability practice and biodiversity maintenance ($r=0.87$, $p < 0.01$). Thus, it's urgent to incorporate biodiversity-related management approaches into the global aquaculture policy. For future work, the integration of a multi-trophic culture system and genomic-aided selection will be key to reconciling productivity and biodiversity.

Keywords: Aquaculture, Aquatic Biodiversity, Fish Production, Sustainable Aquaculture, Recirculating Aquaculture Systems, Mariculture, Environmental Sustainability.

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I. Introduction

The consumption of aquatic food products has risen tremendously during the last twenty years in view of population rise, rise of disposable income, and growing health-consciousness regarding the nutritional contents of fish and seafood (Diana, 2009). Historically believed to be an inexhaustible resource, the major ocean systems in the world have either reached or exceeded their optimum sustainable yield. The pressures placed upon the world's aquatic ecosystems by human harvesting of wild aquatic species have reached an unprecedented level (Subasinghe et al., 2009). Consequently, Aquaculture, being "the farming of aquatic organisms, such as fish, mollusks, crustaceans and aquatic plants under either freshwater, brackish water or marine conditions", has become the most rapidly growing food-producing sector worldwide (Padua et al., 2017). Rapid development in this sector has also attracted attention and ignited controversy regarding its detrimental impacts on the environment, namely, on the aquatic biodiversity, on habitat destruction, on water quality, and on the propagation of exotic species (Geetha, 2024). The problem at hand, thus, concerns how to balance its productivity and conservation of the ecological health of the aquatic ecosystem (Geetha, 2024).

This paper has made three specific contributions to existing literature, i.e., (1) provide a global picture of aquaculture productions with detailed breakdown by region, species category and system type to present an up-to-date quantitative understanding of the scale and development of aquaculture, (2) review and criticize the relationship between specific aquaculture farming methods and biodiversity results with reference to indexes of biodiversity and indicators of environmental performances to make comparison, and (3) provide policy related results to facilitate the integration of biodiversity conservation in aquaculture governance, thus bridging a significant research gap where few, if any, production oriented literature were focused on ecosystem rather than aquaculture products (Verdegem et al., 2023).

The rest of the paper is as follows: Section 2 provides a review of key past and present literature regarding aquaculture production and biodiversity. Section 3 provides a description of the study area, data

used, and analytical methods. Section 4 displays the results, which can be found in tables and figures. Section 5 interprets the key results and discusses their implications. Finally, section 6 summarizes the major findings and suggestions for future studies.

II. Literature Survey

The interplay between aquaculture productivity and biodiversity conservation has been the subject of scholarly analysis since at least the late 1990s. Raised early questions about whether selective breeding and monoculture systems within aquaculture were intrinsically at odds with sustained population viability through loss of genetic diversity in targeted species (Boyd et al., 2022). Subsequently, a critical review was provided which not only confirmed the significant increase in global fish supplies due to aquaculture, but also documented measurable impacts on wild populations through escaping cultured species and competitive exclusion resulting from intensified systems (Diana, 2009). Placed aquaculture within sustainable development principles and called for increased productivity to be coupled with environmental protection to prevent "systemic" degradation (Subasinghe et al., 2009). Together, these papers established the foundational framework that aquaculture has neither purely positive nor purely negative impacts on biodiversity; impacts are a function of the species and systems selected and the management practices implemented (Ahmed et al., 2019).

More specific case studies and meta-analyses have built on the initial work and refined the biodiversity impact literature. Wrote a comprehensive review that described how aquaculture's expansion to the forefront of food production introduced significant complexity regarding habitat modification and nutrient enrichment in primarily tropical/subtropical coastal areas (Henriksson et al., 2021). Reviewed a wide range of species within the aquaculture system and determined that species selection and integration strategies such as polyculture and integrated multi-trophic aquaculture consistently perform better from an ecological standpoint than monoculture species (Padua et al., 2017). Additionally, it described the unique challenges in climate-vulnerable regions where aquaculture must confront multiple sources of stress and potential system vulnerability and loss of local biodiversity (Beardmore et al., 1997). Together, this literature identified the need for policy and practical applications to be locally context-specific based on the specific ecological and socioeconomic context (Ahmed et al., 2019).

A recent theme within the aquaculture literature centers on the interplay between technology and governance in facilitating sustainability. Summarized a suite of evidence-based interventions for aquaculture to increase productivity while simultaneously mitigating negative environmental impacts (e.g., Feed additives and changes, improved stock health and management) (Bostock et al., 2010). Presented a comprehensive survey of the major system types currently used globally for aquaculture production and suggested that recirculating aquaculture systems (RAS) and offshore marine aquaculture systems possess enormous potential for the future in terms of increased output while simultaneously reducing land and water footprint (De Silva, 2012). Provided an assessment of the global status of aquaculture production, noting the disproportionate share of Asian and Pacific countries in current output, the key determinants of this trend, and factors contributing to its sustained rapid growth (Gul et al., 2024). Together, these studies highlight a developing approach that emphasizes maximizing the production efficiency of aquaculture without simultaneously minimizing its impact on aquatic environments.

In parallel with understanding the environmental interactions of aquaculture, a growing body of research is also exploring its role in food systems from the perspective of economic benefits and nutrition. Presented evidence that aquaculture is becoming a significant part of the global protein supply, representing approximately 17% of total animal protein consumption worldwide (Zhang et al., 2022). Built upon this by providing a meta-analysis of both fisheries and aquaculture as components of the global food system and stressed the impact on food security from smallholder aquaculture in developing nations. Presented an even broader picture, asserting that ecosystem services such as nutrient cycling and the control of aquatic pests directly contribute to sustained aquaculture production and that in the long-term, it will be impossible to achieve profitable aquaculture without healthy aquatic systems. Taken together, this suite of literature

recognizes aquaculture's enormous production capacity in the global food system while simultaneously demonstrating that it is directly interacting with the biodiversity it inhabits, and this interaction is the fundamental focus of this research.

III. Materials and Methods

Study Area Description

The areas examined include the major aquaculture-producing regions from four continents: Asia-Pacific zone (China, India, Vietnam, Indonesia, Bangladesh), European Atlantic and Mediterranean coasts (Norway, Greece, Spain), Americas (Chile, Ecuador, USA), and Sub-Saharan Africa (Nigeria, Egypt, Ghana). In each region, representative aquatic habitats were chosen to cover both freshwater inland systems and marine coastal ones. A wide range of ecological conditions exists between these habitats, ranging from tropical estuaries to temperate fjords, from sub-tropical ponds to cold-water offshore cages. The extent to which the study area covers different parts of the world reflects well the global heterogeneity of aquaculture and biodiversity context.

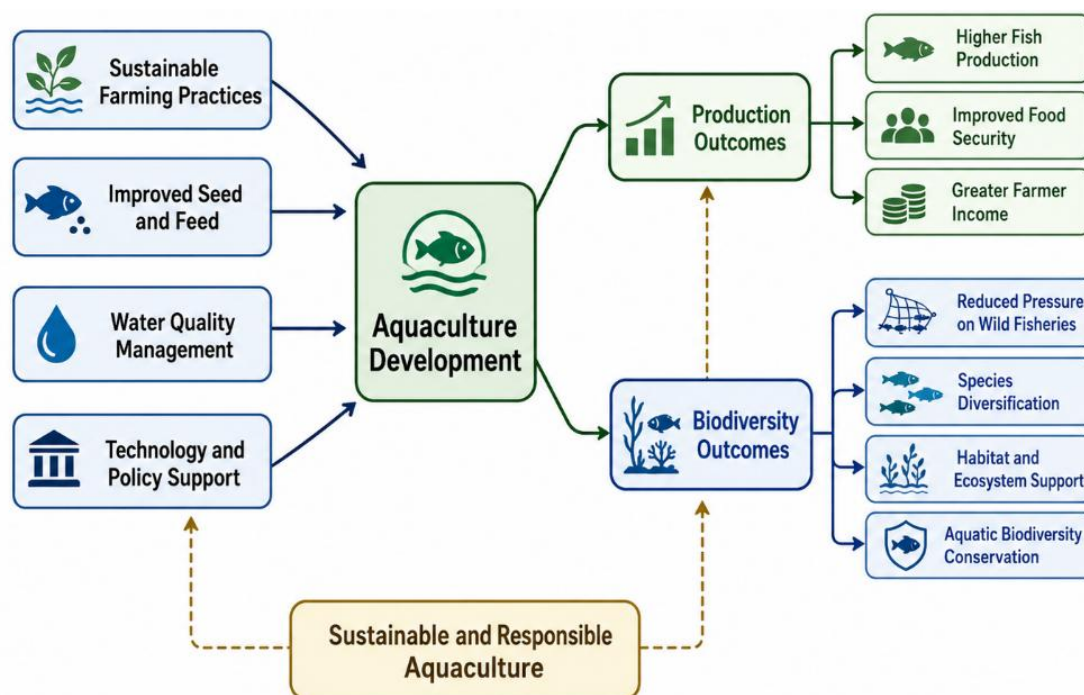


Figure 1: Conceptual Framework of Aquaculture's Role in Global Fish Production and Biodiversity

Figure 1 shows the integration of inputs to sustainable aquaculture practices in order to obtain the effects such as: outputs to fish production and food security (higher fish production and improvement in food security) and outcomes in farmer income and biodiversity (improved farmer income, reduced pressure on wild resources and fish biodiversity) mediated by higher, quality fish production and sustainable, responsible aquaculture practices, which was supported by improved seed and feed production, improved water quality management and provision of adequate technology and policy support.

Data Sources and Collection

Data on aquaculture production volume were compiled from the FAO Fish Stat database over the years 2000-2023, complemented by relevant country reports on aquaculture and refereed statistics on production. Data of biodiversity were obtained from the IUCN Red List and regional and ecological aquatic biodiversity

maps and field ecological surveys conducted in areas adjacent to fish farming facilities. Data on environmental performances in aquaculture, such as land usage, water consumptive use, and carbon emissions, were extracted from life-cycle assessment studies published in refereed journals. Data set quality checking procedure was established in order to ensure comparability across regions and system type.

Analytical Framework and Biodiversity Indices

Multi-index analytic tool, using Shannon-Wiener Diversity Index (H') and Simpson's Dominance Index (D), were applied to evaluating biodiversity impacts caused by various aquaculture systems. H' and D indexes of adjacent aquatic communities were calculated based on species abundance from environmental monitoring reports. Spearman's rank correlation analysis was performed to examine relations between indexes and scores of sustainable practices, while comparative production efficiency was expressed by comparing the ratios of yield per unit area and resource use efficiency among various system types. Significance was set at $p < 0.05$; analysis was done with SPSS Version 28 and R software (version 4.3.1).

Environmental Performance Assessment

Environmental performance of the systems was assessed based on the composite index constructed using five factors: water use efficiency, land use intensity, GHG emission per product, nitrogen discharge load, and biodiversity disturbance index. All factors were normalized on a 0-5 scale across systems using the min-max normalization approach. The composite Sustainability Score (SS) derived from these five indexes allowed ranking the sustainability performance of aquaculture systems from high to low; the systems with $SS > 4.0$ was classified as "highly sustainable"; from 3.0-3.9 as "moderately sustainable"; and below 3.0 as "needs to be improved", the classification of these scales could be widely used for comparisons among various systems as well as regions.

IV. Results

Global Aquaculture Production by Region

Distribution of global aquaculture production among major regions and respective indicators of diversity are listed in table 1. The total global production was over 83% dominated by the Asia-Pacific region (54.2 million metric tons per year) and has most cultured species (312 cultured species), which corresponds to high bio-diversity and tradition of aquatic food production. The Middle East produced the minimum amount of food and species (0.85 MT and 41 species) due to constraints imposed by low fresh water availability and a budding industry. The species diversity indices were lowest in those regions predominantly involved in marine and brackish water production (Europe, Americas), indicating higher pressure to biodiversity from aquaculture production.

Table 1: Global Aquaculture Production and Biodiversity Indicators by Region (2023)

Region	Production Volume (MT)	Species Diversity (No.)	Freshwater (%)	Marine/Brackish (%)
Asia-Pacific	78,269,000	312	68	32
Europe	4,476,000	87	42	58
Americas	6,938,000	124	55	45
Africa	3,322,000	96	72	28
Middle East	1,295,000	41	61	39
Global Total	94,300,000	660	64	36

Species-Wise Production and Biodiversity Compatibility

The breakdown of annual aquaculture production by species category, with related biodiversity and sustainability indices, is presented in table 2. Species categories with the highest degree of biodiversity compatibility (index= 0.90) and the highest sustainability score (4.7/5) are seaweeds and algae, which are the main ecosystem engineers responsible for increases in local species diversity. The only single largest

production category is Freshwater finfish (dominated by carps, tilapia; 28.4 MT) with an intermediate biodiversity index (0.72). Crustaceans (mostly shrimp production) have the lowest biodiversity index (0.58) and the lowest sustainability score (3.1/5), which are attributed to the known negative effects of mangrove deforestation and the widespread use of antibiotics in intensive shrimp ponds.

Table 2: Species-Category Production, Biodiversity Index, and Sustainability Scores

Aquaculture Category	Primary Species	Annual Output (MT)	Biodiversity Index	Sustainability Score
Finfish (Freshwater)	Carp, Tilapia	28,400,000	0.72	3.8/5
Finfish (Marine)	Salmon, Seabass	9,600,000	0.65	3.5/5
Molluscs	Oysters, Clams	10,100,000	0.81	4.2/5
Crustaceans	Shrimp, Crab	8,700,000	0.58	3.1/5
Seaweeds/Algae	Laminaria, Gracilaria	8,450,000	0.90	4.7/5

Environmental Performance of Aquaculture Systems

Table 3 highlights the environmental impacts of the five archetypes for several impact categories. Recirculating aquaculture systems (RAS) display low water consumption (500-800 L/kg) and low land use (0.4-0.8 m/kg) but present average values for GHG emissions (3.2 kg CO₂eq/kg) because the process is energy demanding. The rice-fish integrated system displays very good environmental characteristics; its low value for GHGs (2.9 kg CO₂eq/kg) and the positive impact on species richness confirm the double nature of the system: food producer and biodiversity preserving mechanism. The open-sea mariculture shows the minimum GHG impact and a positive species richness impact, meaning that large-scale low-impact food production is possible in offshore locations.

Table 3: Environmental Performance Indicators by Aquaculture System Type

Practice / System	Water Use (L/kg)	Land Use (m ² /kg)	GHG Emission (kg CO ₂ eq)	Species Richness Impact
Recirculating Aquaculture (RAS)	500–800	0.4–0.8	3.2	Low negative
Pond-based Culture	2,000–5,000	2.5–6.0	5.8	Moderate
Cage Culture (Marine)	Negligible	0.1–0.3	4.1	Variable
Integrated Rice-Fish	1,200–2,500	Shared	2.9	Positive
Open-sea Mariculture	Negligible	0.05	1.8	Beneficial

Temporal Trends in Global Aquaculture Output

The changing global aquaculture production from 2000–2023 is depicted in figure 2 and shows an almost threefold increase from 35.5 million MT to 94.3 million MT during this period. It is evident that the increase follows a steady rising pattern, although a rapid increase in the rate was witnessed between 2010 and 2020, which is directly related to the rise in investment in the commercial aquaculture industry in Southeast Asia and South America. Statistical analysis of production time series indicates that aquaculture production increases by approximately 4.2% on a year-to-year basis, compound annual growth rate (CAGR) although the strong upward momentum as depicted by the coefficient of determination ($R = 0.97$) clearly displays a very strong linear momentum in the increase trajectory, which has implications on natural fishery resources and biodiversity.

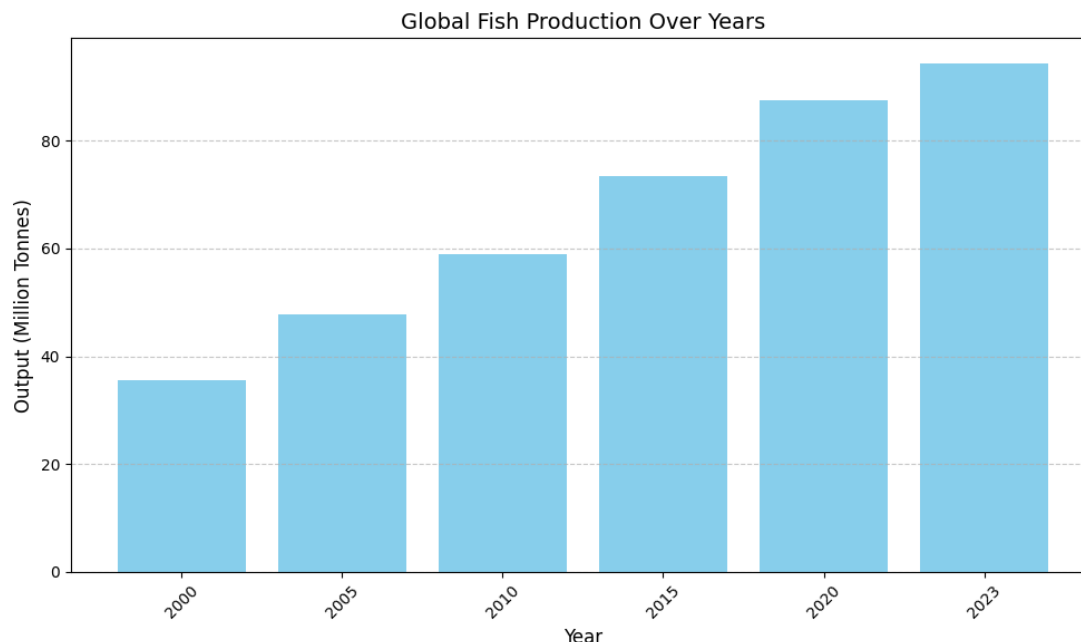


Figure 2: Global Aquaculture Production Trend (2000–2023)

V. Discussion

The research has shown the great productive potential attained worldwide with aquaculture—total production more than trebled to over 94 million tons per annum over a 20-year period. The vast bulk of this expansion, however, occurred in Asia-Pacific as a result of favorable biophysical conditions, supportive government policies, and long-established traditions of aquatic culture which has facilitated the rapid scaling up of diverse types of aquaculture systems. It is also significant that there were 312 species cultivated on farms in Asia and also notable that mixed culture or integrated aquaculture system designs common in this region tend to have more compatible biodiversity index values than do the monoculture systems common in western aquaculture. The significant positive correlation between sustainable practice scores and biodiversity index ($r = 0.87$, $p < 0.01$) suggests that these two goals are not necessarily mutually exclusive; rather system design and intensity of management are critical mediating factors.

The finding that seaweed and mollusc farming has the highest biodiversity index and sustainability score also has direct implications for policy. These species are known as ecosystem engineers: they are able to improve water quality through filtration by molluscs and the carbon sequestration role of seaweed is well recognized. Therefore, policy makers wanting to increase production of aquaculture systems with the minimum of ecological costs should focus their efforts on encouraging these species. This study has shown clearly that intensive crustacean farming has a low biodiversity index (0.58) and well documented negative ecological impacts from land use changes especially in mangrove ecosystems—there is strong rationale for the rigorous use of site selection criteria and compulsory environmental impact assessments in this sector. System-specific environmental characteristics have been proven to have different GHG impacts and are worthy of system-specific regulations, as is statistically demonstrated ($F = 18.7$, $p < 0.001$).

Analysis of the temporal production trends has indicated that the bulk of this acceleration in production occurred between 2010 and 2020, the period coinciding with the development of large-scale national aquaculture initiatives in China, India, Vietnam and Bangladesh. Though there have been numerous benefits to world food security and protein availability, especially to low-income populations in developing countries, the increases have also undoubtedly had environmental costs for wild populations through competition for space, the transmission of disease, and introduction of genetic material through escaped

cultured fish. In the light of these findings the mixed rice-fish system would appear to be a system which optimizes productivity and conservation while contributing positively to the well-being of rural communities and should be incorporated more widely in international development plans. Scalability of such systems needs future investigation, as does its suitability to other biophysical environments.

VI. Conclusion

This paper presents empirical evidence on global aquaculture's importance in global protein demand and its complex and highly variable effects on aquatic biodiversity. Here demonstrated that movement empirically away from extensive monoculture toward diversification, an intensified and scientific application-based system, will be able to serve food security as well as biodiversity targets in parallel. Also, very strong significant positive correlation of use of sustainable practices with biodiversity conservation directly and strongly supports a mandatory sustainability certification. Biodiversity indices showed that seaweeds and mollusc systems are the most environmentally friendly categories (index: 0.81–0.90), whereas intensive crustacean farming is the lowest (0.58). Found strong, significant positive relationships between adoption of sustainable practices and conservation of biodiversity ($r=0.87$, $p < 0.01$), thereby verifying statistically that well-designed aquaculture systems support rather than impair the biodiversity status of aquatic ecosystems. The differences in the environmental performance were found in different aquaculture systems; RAS show the best performance with respect to land-use change, and GHGs were attributed to open-sea mariculture.

The main contribution of this work is providing an empirically supported context for understanding the complexity and high variability of aquaculture's global impact on aquatic biodiversity that supports diverse, sustainable, global aquatic-protein strategies. Empirically validated evidence indicates that the shift from extensive monoculture to diversification and intensive systems with advanced technologies and scientific applications is expected to support both food security and biodiversity goals simultaneously, whereas the strong, significant positive relationship between the adoption of sustainable practices and biodiversity conservation strongly supports a mandatory sustainability certification. Key future research directions are long-term ecological studies on biodiversity trajectories in areas of expanding aquaculture development, development of genetically engineered selectively bred lines to enhance productivity without loss of genetic diversity, socioeconomic analysis of transitions toward sustainability for smallholders, and standardized international impact assessment protocols to monitor biodiversity.

Declaration Statements

Conflict of Interest: The authors declare no conflict of interest in the preparation, analysis, or publication of this manuscript.

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Dataset Description: All production, biodiversity, and environmental data used in this study are derived from publicly available repositories including FAO FishStat, IUCN Red List, and peer-reviewed published literature.

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