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The Role Of Aquaculture In Global Nutrition And Economic Development: A Long Research Article On Challenges, Opportunities, And Future Directions

Ahmed Él salous[1*], Dr. Ashutosh Diwakar[2], Dr Ram Devendra Gudgila[3], Dr. Dipankar Pradhan[4], Dr. Mansi Patil[5], Suranjit Roy[6]
[1*]Universidad Agraria del Ecuador, eelsalous@uagraria.edu.ec 0000-0001-7395-5420
[2]Assistant Professor Department of Zoology Bundelkhand University Campus, JHANSI Email id: ashutoshdiwakar.ft@gmail.com
[3]Assistant Professor, Maharashtra University Of Health Sciences, Nashik Email Id: Id:coachram@ramgudgila.com
[4]Assistant Professor, Faculty of Management and Commerce, The ICFAI University, Tripura, India, Pradhandipankar10@gmail.com https://orcid.org/0009-0006-8818-9451
[5]1- Akshada Clinic, Pune; 2- Hypertension Core Group of IAPEN INDIA Consultant drpatilmansi@gmail.com, Orcid Id: 0000-0002-2337-385X
[6]Research Scholar Assam University, Silchar Email ID: suranjitroy856@gmail.com, 0009-0004-1483-6447

Abstract
Aquaculture has become a crucial part of world food systems, offering sustainable options to satisfy increasing protein needs and boost economic development. This research examines the contribution of aquaculture to nutritional security and economic development and examines major challenges and opportunities influencing its future direction. A mixed-methods approach was taken, incorporating secondary data from global institutions supplemented by thematic review of peer-reviewed articles and chosen country case studies. Findings indicate aquaculture's explosive growth from 17 million metric tons in 1990 to 87 million in 2020, led by Asian production. Nutrient composition of aquaculture species verifies remarkable contributions to protein, omega-3 fatty acids, and vital micronutrients, augmenting dietary diversity. Economic contributions are also substantial, with the industry drawing over USD 263 billion in trading value and employing over 20 million workers globally. However, environmental challenges, disease risks, feed sustainability, and governance loopholes are significant hurdles. Technological advances and equitable policies provide appealing avenues for achieving growth and sustainability. The research highlights aquaculture's capacity to feed people, spur inclusive economies, and promote sustainable development, as long as ecological and social aspects are part of future planning.
Keywords: *Aquaculture, Nutrition Security, Economic Development, Sustainability, Global Food Systems*

INTRODUCTION

Global food security is one of the biggest challenges in the twenty-first century. Sustained population growth, estimated to reach more than 9.7 billion in 2050, combined with urbanization and altering food habits, has heightened the need for good-quality proteins (FAO, 2022). Whereas land animal production has traditionally provided the backbone for fulfilling protein needs, its environmental impact from greenhouse gas emissions to land and water degradation has created sustainability questions (Godfray et al., 2018). As a result, aquatic food systems, and more specifically aquaculture, have appeared as a propitious sector to reduce protein deficiency while being compatible with sustainable development. Fish and other aquatic animals not only yield high-quality protein but also micronutrients like omega-3 fatty acids, zinc, and vitamin D, which are critical for human health and brain growth (Ai et al., 2025). Where malnutrition exists, food from aquaculture can be used as an affordable and available source of nutrition, thus directly leading to better health outcomes and resilience in the food system (Golden et al., 2021).

Aquaculture, rearing aquatic animals under culture systems, has a long history. Early records in China and Egypt reveal practices of fish culture dating back to 2,500 BCE (Garlock et al., 2024). Yet, it was only in the second half of the twentieth century that aquaculture had become a fast-expanding global business. Technological innovations, together with depleted wild fish populations resulting from overfishing, drove its growth (Naylor et al., 2021). Aquaculture has long surpassed other food production industries in rate of growth since the 1980s, recording a mean annual growth rate of almost 6% (FAO, 2022). Aquaculture currently supplies more than half of all aquatic foods eaten worldwide, highlighting its central role in contemporary food systems (Anderson et al., 2017). Though Asia leads the world in production, China alone produces over 60% countries like Africa and Latin America are experiencing steady increases, signifying the sector's widening geographic reach (Farmery et al., 2021).

Nutritionally, aquaculture cannot be overemphasized. Aquaculture products are rich in bioavailable nutrients and do not carry the excessive saturated fats and detrimental fatty acid patterns that accompany many land-based proteins (Kwasek et al., 2020). Apart from nutrition, aquaculture makes an important contribution to the livelihoods worldwide. The industry has direct and indirect employment of millions of women and smallholder farmers who rely on income generation from aquaculture (Belton et al., 2018). Employment covers production, processing, distribution, and retailing, highlighting aquaculture's potential to induce inclusive rural development. Economically, aquaculture is at the heart of global trade. Norway, Vietnam, and Chile have built strong aquaculture export sectors, earning billions of dollars in revenue and making important contributions to GDP growth (Guillen et al., 2019). On the other hand, small-scale aquaculture businesses, especially in low- and middle-income nations, add to domestic food security by providing affordable fish to local markets (Obiero et al., 2018). Consequently, aquaculture not only enhances health and diet variety but also supports national and international economies through job creation, trade revenues, and poverty reduction.

Despite its rapid growth and promise, aquaculture faces intertwined issues compromising its long-term sustainability. Some of the environment-based concerns such as water pollution, habitat degradation, and disease incidence remain, raising the environmental expense of increased production (Stewart-Sinclair et al., 2020). Production of feed remains an important bottleneck, with the consumption of fishmeal and soy-based feed, since it competes with terrestrial farming and puts pressure on natural systems (Chan et al., 2024). Socioeconomic inequalities like unbalanced access to markets, technology, and finance also hinder smallholder farmers from fully benefiting from aquaculture growth. Academic debate also indicates issues of regulation and governance in that poor enforcement and weak and fractured policies impair effective management of aquaculture systems within diverse contexts (Campanati et al., 2021). Secondly, although technology advancements are being widely used to boost efficiency and environmentally sustainable endeavors, they are yet to be taken up uniformly, opening up a gap between small-scale farmers and industrial-scale growers (Naylor et al., 2021).

Objectives

The aim of this study is to examine aquaculture as a source of global nutrition and as an agent of sustainable economic growth, while critically analyzing the environmental, technological, and socioeconomic issues that affect its advancement. It also seeks to determine areas where sustainable intensification is possible and to note successful integration models into global and local food systems. Lastly, the study attempts to suggest policy and research directions to balance productivity with environmental management and inclusive growth.

METHODOLOGY

Research Design and Approach

This mixed-methods research design combined both qualitative and quantitative means of analysis into an integrated view of aquaculture's contribution to world nutrition and economic growth. The quantitative aspect made use of statistical data sets for an examination of trends regarding production, consumption, and trade of aquaculture, while the qualitative aspect does this in combination with scholarly literature and case studies in larger social, economic, and environmental contexts. This design is consistent with food system research, which can require triangulation across different sources of data to capture the complexity of the industry.

Data Collection

The data for this study were acquired from secondary sources. Statistical information was acquired from international databases, including the Food and Agriculture Organisation (FAO), World Bank, and World Health Organisation (WHO), to examine worldwide and regional aquaculture production, trade flows, and nutritional contribution. High-impact peer-reviewed journal articles from journals like Nature, Aquaculture, World Development, and Food Policy were rigorously reviewed to encapsulate existing information on the challenges and opportunities in the sector.

Analytical Framework

Analysis was comparative and thematic in its approach. Initial descriptive statistics and trend analyses were conducted to evaluate aquaculture's role in world fish supply, economic value, and nutritional consumption. Production levels and growth rates were compared regionally to detect inequalities and the scope for scaling. Second, literature was reviewed thematically to reveal common issues like environmental sustainability, feed management, governance, and socioeconomic equity. Coupling quantitative trends with qualitative findings enabled multi-layered analysis, which addressed the interdisciplinary focus of aquaculture research.

RESULTS

Global Production Trends in Aquaculture

Aquaculture production has increased considerably during the last three decades. As stated by FAO (2022), international aquaculture production rose from about 17 million metric tons in 1990 to over 87 million metric tons in 2020, representing a fivefold increase. This growth surpassed the capture fisheries, which have kept relatively stable since the mid-1990s. In Figure 1 illustrates the aquaculture production grew very quickly from 17 million metric tons in 1990 to 87 million in 2020, while capture fisheries leveled off at about 90 million tons. The trend emphasizes aquaculture's shift to become the leading producer of aquatic food, outpacing capture fisheries since 2013 and transforming global food supply patterns.

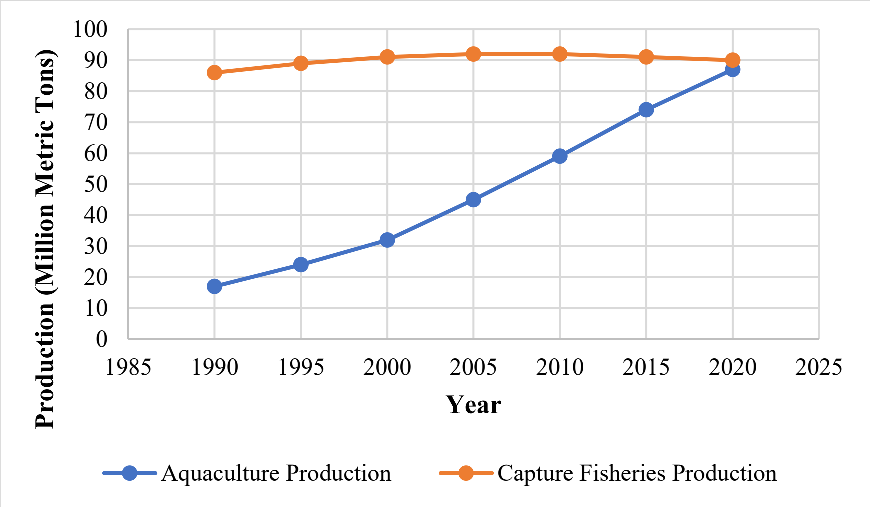

Figure 1: Global Aquaculture vs. Capture Fisheries Production (1990–2020)

Regional Distribution of Aquaculture

Asia has a monopoly on global aquaculture, with almost 89% of overall production in 2020, led by more than 60% from China alone. Other main producers are India, Vietnam, Bangladesh, and Indonesia. Africa produces less than 3% but has recorded the highest growth rate, averaging 10% a year over the past decade. Table 1 depicts regional differences in aquaculture production for 2020. Asia completely dominates with 89% of world production, headed by China and other large producers. Europe and Latin America provide moderate contributions through high-value species such as salmon and shrimp, while Africa demonstrates strong growth despite a relatively small basis of production.

Table 1. Regional Aquaculture Production in 2020 (Million Metric Tons)

Region	Production (MMT)	Share of Global (%)	Main Species Produced
Asia	77.3	89.0	Carp, tilapia, shrimp, catfish
Europe	4.1	4.7	Salmon, trout, seabass
Latin America	3.0	3.4	Salmon, shrimp, tilapia
Africa	2.6	3.0	Tilapia, catfish, freshwater fish
North America	0.7	0.8	Salmon, catfish

Contribution to Global Nutrition

Aquaculture has emerged as a vital source of animal protein and micronutrients. On average, fish contribute 17% of world animal protein consumption and more than 50% of small island developing state consumption. Nutrient analyses indicate that aquaculture-produced species like carp and tilapia supply cheap protein, while salmonids and shellfish supply higher concentrations of essential fatty acids and micronutrients. Figure 2 illustrates nutrient diversity in aquaculture species. Salmon supplies the highest in omega-3 and vitamin D, while carp and tilapia supply cheap, protein-dense food. Oysters are outstanding in being rich sources of zinc and

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vitamin B12. Both these species show aquaculture's potential to produce varied, nutrient-rich food critical for world nutrition.

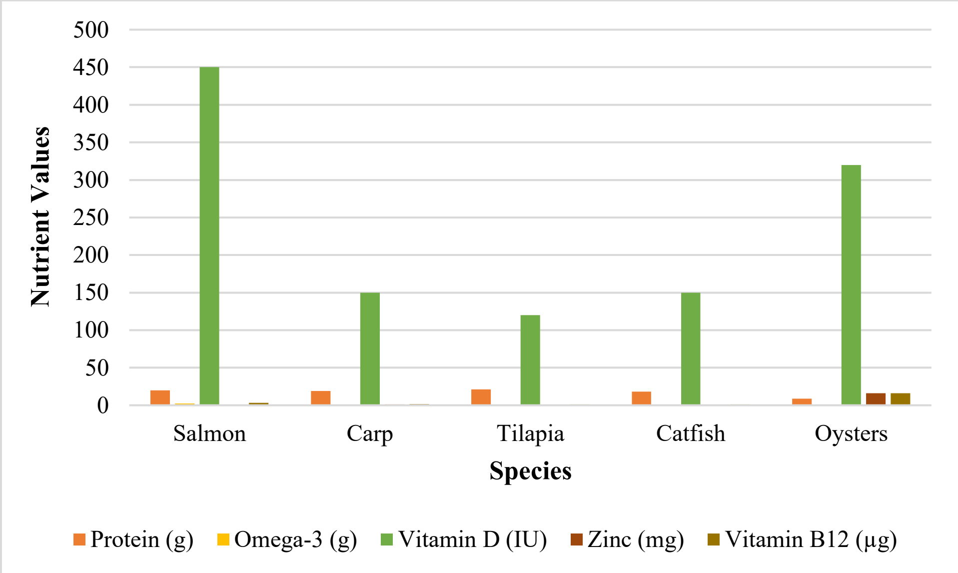

Figure 2: Nutrient Profiles of Key Aquaculture Species (Protein, Omega-3, Vitamin D)

Economic Contributions

Economic importance of aquaculture has grown in line with production expansion. International aquaculture trade in 2020 amounted to USD 263 billion, with valuable exports like shrimp and salmon dominating revenues. Employment within the aquaculture value chain exceeds 20 million individuals worldwide, the majority working in small- and medium-scale businesses. Table 2 illustrates aquaculture's economic contributions in main producing countries. China leads with the highest employment base, while Bangladesh and Vietnam exhibit stronger GDP shares fueled by smallholder engagement and exports. Norway and Chile indicate developed, export-driven salmon industries with substantial revenues corresponding to lower employment numbers, indicating different production structures globally.

Table 2. Aquaculture Contribution to GDP and Employment in Selected Countries

Country	Aquaculture GDP Share (%)	Employment (Million)	Key Export Products
China	1.6	14.0	Carp, tilapia
Norway	0.8	0.04	Salmon
Bangladesh	2.2	3.5	Shrimp, carp
Vietnam	1.9	3.0	Shrimp, pangasius
Chile	0.7	0.1	Salmon, trout

DISCUSSION

The findings of this research identify aquaculture's impressive growth path, with it being the fastest developing food production industry in the world. The growth from 17 million metric tons in 1990 to 87 million metric tons in 2020 indicates aquaculture's rising capacity to provide global food requirements (FAO, 2022). In contrast to capture fisheries, which leveled off at about 90 million metric tons over the same time frame, aquaculture has moved beyond natural supply thresholds by ramping up production under controlled systems. This transition is in line with a broader structural transition in food systems, where controlled aquatic production is now an essential link between bridging the protein gap and fulfilling food security needs (Anderson et al., 2017). This type of transition is particularly important in the context of sustainable development. As animal agriculture on land is brought under scrutiny for its high greenhouse gas and land use (Godfray et al., 2018), aquaculture is a comparatively resource-frugal alternative. Fish and seafood products possess superior feed-to-gain ratios, reduced carbon intensities, and produce nutrient profiles very challenging to be outdone by land-based proteins (Kwasek et al., 2020). Data confirms that aquaculture is not only an addition but a building block of future nutrition strategies.

Asia's near 89% dominance of aquaculture production points to the geographical concentration of aquaculture (Farmery et al., 2021). Although Asia's prosperity is attributed to cultural appetites, government spending, and established supply chains, the gap with other regions points to structural imbalances in global food production. Africa, accounting for less than 3% of global aquaculture production, has the highest growth rates, with an average annual growth of 10%. This suggests high underlying potential for growth, if challenges like poor infrastructure, fragile governance, and limited access to credit are overcome (Obiero et al., 2018). Latin America and Europe can be described as opposite models of specialisation. Latin America, particularly Chile, has been a powerhouse exporter in salmon and shrimp farming, while Europe has focused on technological innovation and regulatory systems, especially in Norwegian salmon aquaculture (Guillen et al., 2019). These differences point out that aquaculture is not one-size-fits-all but is influenced by environmental, cultural, and institutional factors. Copying successful models calls for adjustment and not across-the-board transfer, especially in places such as Africa and South Asia, where smallholder involvement is prevalent.

The results reiterate aquaculture's fundamental role in international nutrition. On average, fish contribute 17% towards international animal protein consumption, with some small island developing nations relying on aquatic foods for more than half of their protein requirements (Golden et al., 2021). The diversity of nutrients between species, as shown in Figure 2, demonstrates aquaculture's singular contribution of offering both low-cost staples like carp and tilapia and nutrient-rich foods like salmon and oysters. Notably, aquaculture not only provides macronutrient security but also helps to address micronutrient deficiencies, a condition referred to as "hidden hunger." Oysters are a notable example that offers superior amounts of zinc and vitamin B12, while salmonids provide omega-3 fatty acids that are crucial to cardiovascular and cognitive health (Ai et al., 2025). Aquaculture's double contribution speaks to its ability to work toward Sustainable Development Goal 2: Zero Hunger, addressing both calorically and micronutrient-related deficiencies. But access is still unequal. In most low-income areas, aquaculture commodities are still priced out of the market for the very poor households. Policies to support local markets, curtail export-led inflation, and bring aquaculture into nutrition-sensitive programs can help bridge these gaps (Obiero et al., 2018).

Aquaculture's economic contribution goes beyond nutrition, with trade worth USD 263 billion in 2020 and jobs for more than 20 million individuals (FAO, 2022). Table 2 points out the variety of contributions: while China leads by magnitude, Bangladesh and Vietnam illustrate how aquaculture can significantly contribute to GDP and rural livelihood. Bangladesh's instance, which offers 2.2% of GDP and generates employment for 3.5 million employees, is a testament to its potential towards poverty alleviation and inclusive growth (Belton et al., 2018). On the other extreme, Norway and Chile feature high-value, export-oriented models, focusing on quality, efficiency, and innovation. Such models provide high revenues with relatively low employment levels, indicating the economic specialization capability of the sector. However, these export-driven approaches likewise carry risks of external dependency on global markets, which could put producers at the mercy of world price fluctuations (Guillen et al., 2019). The gender aspect is just as significant. Women contribute greatly to post-harvest processing, marketing, and small-scale aquaculture, only their contributions are not highly valued. Mitigating gender disparities through capacity building, access to credit, and participation in decision-making can also increase aquaculture's developmental impact (Belton et al., 2018).

While no one denies aquaculture's value, its massive growth has created environmental trade-offs. Intensive culture of shrimp has led to mangrove deforestation in Southeast Asia, and aquaculture for salmon in Norway and Chile have reported recurring sea lice infestations that can destabilize the ecosystem (Naylor et al., 2021). These issues highlight the aquaculture paradox: it offers sustainable alternatives to terrestrial protein but its practices can devastate aquatic ecosystems if not regulated. Disease outbreaks are another key challenge. Figure 3 shows the occurrence of big aquaculture diseases like White Spot Syndrome in shrimp and Tilapia Lake Virus in Africa. Such diseases not only lead to economic losses but also food insecurity, especially where aquaculture is a significant source of protein (Stewart-Sinclair et al., 2020). Biosecurity enhancement, investment in vaccines, and implementation of genetic enhancements are crucial in addressing such vulnerabilities. Feed sustainability is also a contentious issue. Aquaculture's dependence on fishmeal and soy inputs causes competition with land-based agriculture and adds extra pressure on the marine environment (Chan et al., 2024). Developments in feed, such as algae, insects, and crop by-products, are potential solutions but need to be scaled up and made less expensive to be genuine alternatives (Ai et al., 2025).

The findings highlight governance as a determining factor in the sustainability of aquaculture. Diverse policies, weak regulation, and inefficient enforcement dislocate long-term performance (Handoyo, 2024). Farmery et al. (2021) mention that good governance is needed to balance environment conservation with economic development, but most countries do not have harmonized frameworks. The Norwegian licensing system, which tightly controls environmental carrying capacity, is a model of best practice. Conversely, countries with poor governance experience overstocking, disease spread, and market imbalances. Globally, trade governance is complicated. While revenue is generated by aquaculture exports, there are concerns regarding sustainability standards, certification, and traceability (Campanati et al., 2021). Standardizing worldwide standards and maintaining fair trade practices can curb inequities and build consumer trAquaculture's future depends heavily on innovation. Recirculating aquaculture systems (RAS) reduce water consumption by up to 95%, while integrated multi-trophic aquaculture (IMTA) enhances ecosystem efficiency by recycling nutrients across species (Garlock et al., 2024). Digital technologies such as artificial intelligence, sensor-based monitoring, and blockchain for traceability are increasingly being applied to improve efficiency and transparency (Ellahi et al., 2023). Yet, technological adoption remains uneven. While industrial producers in developed nations integrate cutting-edge solutions, smallholder farmers in developing countries often lack access to technology, capital, and training (Naylor et al., 2021). Bridging this digital divide requires targeted investments, capacity-building programs, and public-private partnerships.

The integration of evidence highlights the necessity for multi-scalar policy action. Nationally, policies need to support fair access to technology, credit, and markets for smallholders (Clay & King, 2019). Regionally, infrastructure investment and value chain development can make countries more competitive and food available (Kovshov et al., 2023). Internationally, globally applicable standards for sustainability and trade can promote fair engagement and consumer confidence. Critical, however, is that policies will take a food systems approach, which will incorporate aquaculture along with agriculture, nutrition, and environmental planning (Hebinck et al., 2021). In this integrated manner, aquaculture will help not only in economic development but also in enhanced health benefits and ecological resilience (Chan et al., 2024).

Limitations

The current research, though exhaustive in scope, is limited by the use of secondary data sources such as FAO, World Bank, and peer-reviewed literature. Such reliance constrains the capacity to confirm the consistency and accuracy of reported aquaculture production statistics, especially in low- and middle-income nations where data on aquaculture tend to be incomplete or underreported. The application of case studies, while informative, fails to reflect the complete range of aquaculture systems globally, potentially leading to bias toward well-documented regions like Europe and Asia. In addition, mixed-methods design focuses on trends and thematic synthesis without primary field-based validation, which can limit contextual richness. Such limitations infer caution when generalizing results to varied ecological, cultural, and institutional settings.

Future Directions

Longitudinal, field-based research integrating nutritional, economic, and environmental assessments is the way forward for research that will capture more comprehensively aquaculture's systemic impacts. More data collection in previously underrepresented regions, particularly Africa and small island developing states, is critical to improve global estimates. Research into alternative feeds, disease management strategies, and climate-resilient production systems must be accelerated to reduce environmental trade-offs. Furthermore, integrated strategies bringing aquaculture together with agriculture, public health, and policy can contribute to elucidating its role in sustainable food systems. Specific attention should be given to smallholder-inclusive policy and gender-responsive interventions to ensure equitable benefits. Closing knowledge gaps, future studies can support policies that align aquaculture development with international nutrition and sustainable development goals.

CONCLUSION

Aquaculture has demonstrated unparalleled capacity to reshape food systems by bridging the distance between nutritional need and limited capture fisheries. Growth in the industry has reshaped global supply patterns, and aquatic foods have become a requirement for dietary variety and micronutrient adequacy. The evidence shows that aquaculture provides not only cheap proteins such as carp and tilapia but also nutritionally rich products such as salmon and oysters, adding omega-3 fatty acids, zinc, and vitamin B12 to human diets. Beyond food, aquaculture generates employment, export revenues, and rural livelihoods, as exemplified in alternative models of smallholder-led systems in Bangladesh and export-led salmon aquaculture in Norway and Chile. But the research also reveals the environmental and social trade-offs of intensive aquaculture systems. Habitat destruction, disease, and dependency on fishmeal-based diets highlight the ecological cost of growth. Unbalanced access to markets and technology expose the persistent socioeconomic divide between large-scale farms and smallholders. Overcoming these challenges demands reforms in governance, climate-resilient feed innovations, and funding for climate-resilient technologies. The course of aquaculture in the future hinges on policy that considers nutrition objectives, equity, and environmental protection. At the nexus of food security and economic growth, aquaculture presents an avenue for resilient, inclusive, and sustainable food systems that can feed world populations in the coming decades.

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