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Sustainable Aquaculture Practices: Balancing Economic Viability and Environmental Integrity in Developing Nations

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Abstract
This paper presents a critical evaluation of sustainable aquaculture practices in developing nations, with particular emphasis on achieving a balance between economic viability and environmental integrity. Given aquaculture's expanding importance in global food systems—especially in regions confronting the overexploitation of capture fisheries—the study synthesises scholarly literature, institutional reports, and illustrative case studies from Nigeria, other African countries, and international contexts. Employing a thematic review approach, it explores interlinked dimensions, including socio-economic contributions, environmental stewardship, governance, technological innovation, equity, and climate resilience.
The findings indicate that sustainable aquaculture is inherently multidimensional, requiring the integration of ecological management, market competitiveness, and social inclusivity. On the economic front, growth is driven by increasing domestic consumption, burgeoning export opportunities, and technological advancements, yet hindered by high input costs, inadequate infrastructure, and inefficiencies along the value chain. Socially, aquaculture strengthens food security and supports livelihoods; however, structural inequalities, particularly those affecting women and marginalised groups, remain pervasive. Environmental sustainability is contingent upon efficient waste management, conservation of aquatic habitats, and adaptive responses to the impacts of climate change. Furthermore, coherent policy and institutional frameworks—together with effective monitoring, certification, and traceability mechanisms—are essential for aligning production processes with both ecological requirements and market expectations.
The study concludes that advancing sustainable aquaculture in developing nations demands a holistic strategy that harmonises economic performance, environmental responsibility, and social equity. It recommends strengthening integrated policy frameworks, enhancing capacity-building initiatives and extension services, incentivising eco-innovations, improving smallholder access to certification, and incorporating indigenous knowledge systems and gender-responsive approaches into sectoral planning. Implemented effectively, such measures can enable aquaculture to become a resilient, inclusive, and environmentally responsible pillar of national development and a significant contributor to global food security.

Keywords: Sustainable Aquaculture, Developing Nations, Environmental Integrity, Economic Viability, Climate Resilience, Gender Equity

1. Introduction

Aquaculture has emerged as one of the most rapidly expanding food production sectors globally, offering a promising pathway towards enhanced food and nutritional security, particularly in developing nations. As the demand for aquatic protein continues to escalate amidst stagnating capture fisheries and rising population pressures, aquaculture presents a critical opportunity to bridge the widening supply–demand gap (FAO, 2020; FAO, 2022). Yet, the growth of the sector in developing regions presents a multifaceted challenge, centred on the need to balance economic viability with the protection of environmental integrity. Within this framework, sustainable aquaculture emerges not simply as a technical objective but as an essential socio-political and ecological priority (Campanati *et al.*, 2022) [20].
The evolution of aquaculture in regions such as Sub-Saharan Africa and Southeast Asia reveals a mix of promise and concern. In Nigeria, for instance—one of Africa's foremost aquaculture producers—both smallholder and commercial fish farming have

expanded considerably. However, the sector still faces persistent challenges, including poor feed quality, environmental degradation, and inadequate infrastructure, all of which constrain its long-term sustainability (Adeosun *et al*., 2021). Similar systemic constraints are evident elsewhere on the continent. In Kenya, persistent challenges related to feed supply chains, farmer technical capacity, and weak regulatory oversight have been widely reported (Opiyo *et al*., 2018) [46], underscoring the urgent need for targeted policy and practice reforms.

Globally, while aquaculture has contributed substantially to fish supply, concerns about its ecological footprint—ranging from nutrient enrichment and water pollution to habitat loss and genetic interactions with wild stocks—continue to provoke debate over its long-term viability (Naylor *et al*., 2021; Froehlich *et al*., 2022) [43, 33]. The key challenge lies in aligning sectoral growth with ecosystem-based management principles that promote biodiversity conservation, reduce waste, and limit antimicrobial and chemical inputs. As emphasised by Ottinger *et al*. (2022), aquaculture's future will depend on its ability to operate within ecological boundaries while delivering equitable social and economic benefits.

Certification schemes and best management practices are increasingly promoted as means of aligning economic objectives with environmental stewardship. Programmes such as the Aquaculture Stewardship Council (ASC) and Best Aquaculture Practices (BAP) are designed to reassure markets and consumers that production adheres to recognised sustainability benchmarks (Saha *et al*., 2022) [53]. However, their applicability in developing country contexts remains contested, as financial, administrative, and technical barriers often limit the participation of small-scale producers (Rector *et al*., 2023) [50]. Without strong governance and locally tailored implementation, certification risks becoming a nominal exercise rather than a genuine driver of transformative change.

Integrating indigenous ecological knowledge and community-based governance into aquaculture management is equally vital for achieving sustainability. In numerous rural settings, traditional practices inform decisions on site selection, stocking densities, and pond construction. However, such approaches are frequently overshadowed by externally developed models that may not align with local socio-economic contexts (Harrison, Rybråten and Aas, 2018) [36]. Genuine sustainability requires participatory governance that harmonises scientific innovation with the wisdom embedded in local traditions.

Food and nutrition security also remain central to sustainable aquaculture discourse. Fish provides essential protein and micronutrients to millions, particularly in low-income settings (FAO, 2022). Strategies for sustainability must therefore prioritise equitable access and affordability, shifting from purely export-oriented models to approaches that also strengthen local markets and employment.

Climate change compounds these challenges. Altered precipitation regimes, extreme weather events, and rising water temperatures threaten aquaculture productivity and viability (Ahmed *et al*., 2019 [5]; Ottinger *et al*., 2022). Climate-resilient systems, improved feed and seed technologies, and adaptive co-management are therefore critical.

Finally, international agencies and research networks continue to play pivotal roles in capacity building, policy development, and global benchmarking. Yet, translating global frameworks into context-specific, locally owned solutions remains uneven, particularly in fragile and resource-constrained states (FAO, 2022). Achieving sustainability will require coordinated action across certification, innovation, education, and governance—pillars that are interdependent and must be adapted to local realities.

This review is guided by the central aim of examining how developing nations can implement sustainable aquaculture practices that harmonise economic viability with environmental integrity. Its objectives are to synthesise empirical and conceptual insights from diverse regions, identify enabling conditions and constraints, and highlight innovations and governance approaches that support sustainability. The scope encompasses inland and coastal systems, smallholder and commercial enterprises, and varied governance regimes, offering a holistic, evidence-based foundation for policymaking, sustainable development planning, and research.

2. Foundations of Sustainable Aquaculture in Developing Nations

Aquaculture has become a cornerstone of modern food systems in developing nations, presenting both economic opportunity and environmental risk. As the demand for aquatic protein escalates in tandem with population growth and declining wild fish stocks, aquaculture is increasingly framed as a viable strategy to bolster food security, create employment, and drive rural development (Williams, 1997) [59]. However, without firm foundations rooted in sustainability, this promise risks being undermined by ecological degradation, socio-economic inequality, and institutional fragility. Establishing solid foundations for sustainable aquaculture requires a holistic understanding of interconnected ecological, institutional, social, and economic dimensions.

At the ecological level, the sustainability of aquaculture systems hinges on their compatibility with the natural environment. Conventional models, particularly those driven by export markets, have too often prioritised productivity over environmental integrity, resulting in nutrient pollution, habitat destruction, and biodiversity loss (Rivera-Ferre, 2009) [51]. In contrast, Costa-Pierce (2010) [23] argues for the development of ecological aquaculture systems, which integrate farming practices within the carrying capacity of the local ecosystem, utilising nutrient loops, polyculture techniques, and native species. Such models are not only environmentally robust but also socially embedded, respecting local culture, knowledge systems, and ecological limitations.

In Nigeria, aquaculture has experienced significant growth, driven by increased demand and government interest. Yet, many systems remain extensive or semi-intensive and lack environmental safeguards. As Akinrotimi, Abu, and Aranyo (2011) [6] caution, the continued use of unsustainable inputs and poor waste management practices could render the sector environmentally and economically untenable. These authors advocate for the adoption of environmentally-friendly aquaculture practices that incorporate sedimentation ponds, water recycling, and locally-sourced feed to mitigate impacts on adjacent ecosystems and water bodies.

Similar patterns can be observed in Kenya, where aquaculture development has been impeded by challenges in feed formulation and pond management. Munguti, Charo-Karisa, and Opiyo (2014) stress the importance of research and capacity building, noting that while the Kenyan government has made strides in establishing hatcheries and training programs, more is needed to standardise feed quality and enhance nutrient utilisation. Feed sustainability, in particular, remains a critical challenge in developing countries, where access to high-quality protein sources such as fishmeal is often limited or environmentally detrimental. The push toward alternative feed ingredients, such as insect meal and agricultural by-products, is a promising avenue that must be scaled responsibly.

Institutional support plays an equally vital role in anchoring sustainable aquaculture. Regulatory frameworks that define water use rights, environmental monitoring, and biosecurity protocols are crucial, yet often underdeveloped in many low- and middle-income countries (Boyd, D'Abramo & Glencross, 2020) [14]. Institutional voids create space for exploitative practices and limit the enforcement of standards. Hambrey (2017) [35] underscores the need for multi-stakeholder coordination aligned with the 2030 Sustainable Development Goals, suggesting that national aquaculture strategies must harmonise environmental sustainability with poverty alleviation and gender equity.

Social dimensions are equally foundational. For aquaculture to be truly sustainable, it must serve as a vehicle for inclusive development. In many rural communities, aquaculture offers a rare opportunity for income diversification, particularly for women and youth. However, the benefits are not evenly distributed. Bunting (2024) notes that unless social equity is embedded within aquaculture design and governance, marginalised groups may be excluded or exploited, especially in commercial value chains dominated by capital-intensive firms. Community-based aquaculture and cooperative models have been shown to improve collective bargaining, foster local stewardship, and promote equitable benefit sharing.

Economic sustainability, often the most visible metric, should not eclipse these other dimensions. While profitability is essential to the viability of aquaculture enterprises, it must be viewed in terms of long-term resilience rather than short-term gains. Bosma and Verdegem (2011) [12] emphasise that low-input systems that recycle nutrients and use renewable energy may offer more sustainable profit margins than intensive systems reliant on imported inputs and antibiotics. Moreover, economic foundations must consider externalities—costs borne by communities or ecosystems—that are often excluded from conventional accounting.

One of the fundamental critiques of export-oriented aquaculture in developing regions is its disconnection from local food systems. Rivera-Ferre (2009) [51] highlights how shrimp farming, while lucrative in foreign exchange terms, has often displaced small-scale farmers and degraded coastal ecosystems, with minimal reinvestment in local economies. To avoid repeating these patterns, aquaculture must be repositioned within broader rural development strategies that enhance local food access, support smallholders, and prioritise ecological stewardship.

Looking forward, the foundations of sustainable aquaculture must be reinforced through adaptive learning, participatory research, and innovation. As Boyd, D'Abramo, and Glencross (2020) [14] argue, the future of aquaculture depends on our ability to balance environmental thresholds, economic opportunity, and social responsibility. This requires not just technical expertise but also visionary leadership, effective institutions, and community-driven approaches. The success of sustainable aquaculture in developing nations will ultimately be measured not by tonnage alone, but by the resilience, inclusivity, and ecological integrity of the systems it nurtures.

2.1 The Socioeconomic Significance of Aquaculture

Aquaculture has emerged as a critical lever for socioeconomic transformation in many developing nations, serving as a vital instrument in advancing food security, poverty alleviation, employment generation, and inclusive rural development. As wild capture fisheries face stagnation and decline, aquaculture is increasingly recognized for its potential to fill the nutritional and economic void, particularly in regions where dependence on aquatic protein is culturally and nutritionally entrenched (Ahmed & Lorica, 2002) [2].

In socioeconomically vulnerable contexts, aquaculture contributes both directly and indirectly to livelihood enhancement. Direct contributions include employment opportunities in fish farming, hatchery management, feed distribution, and market logistics. Indirect benefits are realised through multiplier effects on ancillary industries and services, including transport, processing, and retail. Pomeroy, Dey, and Plesha (2014) [48] observed that aquaculture's ability to catalyse semi-intensive, small-scale entrepreneurship is particularly beneficial in rural and peri-urban zones with limited industrial infrastructure. In Bangladesh and other Asian countries, small indigenous fish species cultivated through integrated polyculture systems have proven effective in enhancing household nutrition and diversifying income sources.

In Sub-Saharan Africa, aquaculture's socioeconomic relevance is becoming increasingly pronounced. Nigeria exemplifies this trend, where aquaculture has transformed from a marginal economic activity to a central pillar in national food production strategies. According to Akinrotimi, Abu, and Aranyo (2011) [6], smallholder aquaculture in Nigeria not only improves protein intake but also provides a reliable income stream in the face of fluctuating agricultural yields and climate instability. However, the sector still faces critical bottlenecks, such as high feed costs, poor hatchery performance, and limited extension services, all of which hinder its full socioeconomic potential.

The role of aquaculture in addressing chronic poverty has been extensively examined. Edwards (2000) [27] posits that while aquaculture may not universally alleviate poverty, it holds notable promise when embedded in appropriate institutional and environmental contexts. His analysis suggests that targeted interventions—such as improved access to credit, secure land tenure, and inclusive extension services—are essential for marginalised groups, particularly women and youth, to benefit equitably from aquaculture-led growth. Moreover, aquaculture can significantly contribute to social capital formation, especially when organised around cooperative models or farmer associations that promote collective action and resource sharing.

The significance of aquaculture also extends to national and regional economies through its contribution to GDP, export earnings, and rural revitalisation. Samaddar (2022) [54] highlights the case of Tilapia aquaculture in several tropical countries, where both monoculture and polyculture systems have created competitive domestic markets and supported export opportunities. Nonetheless, he cautions that the balance between local food security needs and export-oriented growth must be carefully negotiated to avoid compromising household nutritional outcomes, particularly for lower-income communities.

Despite these benefits, the socioeconomic implications of aquaculture are not universally positive. The expansion of industrial, export-focused aquaculture—especially shrimp farming—has sparked considerable controversy due to its displacement of small-scale farmers and alteration of traditional livelihoods (Primavera, 1997) [49]. In many cases, land appropriation and ecological degradation associated with such developments have triggered social tensions and exacerbated inequality. Primavera warns that unless sustainability is interpreted holistically—accounting for environmental, economic, and social dimensions—the gains from aquaculture may disproportionately accrue to elites, leaving vulnerable groups further marginalised.

Another layer of complexity arises when considering the cultural and gender dimensions of aquaculture. Tisdell (1994) [55] argues that imported aquaculture technologies often fail to align with local socio-cultural contexts, leading to low adoption rates or inequitable benefit distribution. Women, for example, may be excluded from access to inputs or decision-making processes despite playing central roles in post-harvest handling and small pond management. Integrating gender-responsive frameworks and participatory research methodologies into aquaculture policy and practice can therefore help ensure that its socioeconomic contributions are both inclusive and resilient.

Food security remains a cornerstone of aquaculture's socioeconomic justification. E-Jahan, Ahmed, and Belton (2010) [28] demonstrate that aquaculture interventions in Bangladesh not only enhance fish consumption but also contribute to household income stability, particularly when designed to include resource-poor farmers. Their study confirms that integrated approaches—combining nutrition education, input provision, and market access—can magnify aquaculture's impact on poverty reduction and nutritional outcomes. Similar findings across various developing contexts affirm aquaculture's capacity to function as both a livelihood and nutrition strategy, provided the necessary institutional and infrastructural enablers are in place.

2.2 Environmental Considerations in Aquaculture Practices

Aquaculture, while increasingly recognised as a solution to global food insecurity, has also been implicated in a host of environmental challenges that threaten to compromise its long-term viability. As the sector expands rapidly in developing nations, environmental sustainability must be embedded at the core of aquaculture policies, practices, and governance frameworks. This is particularly essential in countries where regulatory enforcement is weak and ecological systems are already under pressure from population growth, industrialisation, and climate change.

One of the most pressing environmental concerns associated with aquaculture is eutrophication caused by excessive nutrient loading from uneaten feed, fish excreta, and chemical inputs. In Nigeria, where aquaculture is dominated by earthen ponds and semi-intensive systems, environmental degradation has become increasingly evident. According to Akinrotimi, Abu, and Aranyo (2011) [6], many farms discharge untreated effluents directly into local water bodies, causing oxygen depletion, algal blooms, and aquatic biodiversity loss. The authors argue for the adoption of environmentally friendly technologies such as effluent retention ponds, organic feed practices, and the reuse of pond water to reduce contamination levels and ensure ecological compatibility.

This challenge is not confined to Nigeria. Throughout sub-Saharan Africa, aquaculture is frequently established in environmentally sensitive zones—such as wetlands, lakeshores, and mangrove ecosystems—often without thorough environmental impact assessments. In a review of environmental policies across the continent. Mapfumo (2022) [41] observed that although legal frameworks are in place, their enforcement is generally weak due to institutional fragmentation, inadequate funding, and limited technical capacity. Such regulatory shortcomings enable unsustainable practices to persist, including excessive antibiotic use, the introduction of invasive species, and inappropriate site selection. The study advocates for strengthened environmental governance, improved cross-sectoral policy coordination, and increased engagement of local communities in ecological monitoring.

Globally, the environmental footprint of aquaculture has been a subject of intense scrutiny. Troell *et al.* (2014) [56] contend that if appropriately managed, aquaculture can actually contribute to global food system resilience, particularly when integrated with agriculture and ecosystem services. However, in the absence of such integration, intensive systems—especially cage culture and shrimp farming—have been associated with mangrove destruction, water salinisation, and disruption of local hydrological cycles. In many coastal regions of Asia and Latin America, these impacts have eroded natural buffers against storms and rising seas, thereby exacerbating vulnerability to climate change.

Innovative solutions are emerging to mitigate such impacts. The concept of Integrated Multi-Trophic Aquaculture (IMTA), which combines species from different trophic levels (e.g., fish, shellfish, and algae), offers one example of how nutrient cycles can be closed to reduce waste and improve environmental performance. Similarly, mangrove-integrated shrimp cultivation has shown promise not only for maintaining ecological integrity but also for sequestering significant amounts of blue carbon. Ahmed, Thompson, and Glaser (2019) [5] present compelling evidence from Bangladesh, where integrated systems have enhanced local biodiversity, reduced disease outbreaks, and improved the carbon footprint of aquaculture. Although such practices require careful planning and training, they present viable pathways for countries with fragile coastal ecosystems.

Another critical aspect of environmental sustainability in aquaculture is the choice of species and feed inputs. Boyd, D'Abramo, and Glencross (2020) [14] caution against the heavy reliance on wild-caught fishmeal and fish oil, which creates a paradox of extracting wild resources to feed farmed ones. This practice places additional strain on marine ecosystems and undermines the ecological logic of aquaculture. The authors advocate for the use of alternative protein sources such as soybean meal, insect-based proteins, and microbial biomass, which can substantially reduce pressure on wild fish stocks. However, they note that the adoption of such alternatives in developing countries is often constrained by cost, availability, and cultural preferences.

Environmental considerations must also be localised. Diana *et al*. (2013) [25] argue that sustainable aquaculture is not a one-size-fits-all endeavour. Ecosystem characteristics, carrying capacities, and socio-cultural contexts vary greatly across regions, and environmental strategies must be tailored accordingly. In regions with limited freshwater availability, for instance, closed-loop systems such as Recirculating Aquaculture Systems (RAS) may offer a water-efficient alternative, though their high capital and energy requirements may limit scalability in low-income settings. Conversely, in floodplain ecosystems, seasonal pond aquaculture aligned with natural hydrological cycles can be both sustainable and cost-effective.

Equally important is the need for environmental literacy among farmers and aquaculture stakeholders. Bunting (2013) emphasises the role of education, participatory learning, and community-based resource management in fostering environmental stewardship. Where farmers understand the ecological consequences of their practices, they are more likely to adopt preventative and adaptive measures. Unfortunately, in many parts of the developing world, extension services are poorly developed, and knowledge transfer mechanisms are weak or absent. This not only hinders innovation but also perpetuates environmentally damaging practices born out of necessity or misinformation.

2.3 Economic Drivers and Market Dynamics

Aquaculture in developing nations is shaped by an intricate interplay of economic drivers and market dynamics, which together determine the sector's capacity to contribute to food security, poverty alleviation, and broader socio-economic transformation. Economic drivers encompass demand-side and supply-side factors—ranging from consumer preferences and income growth to input costs, infrastructure availability, and policy incentives—while market dynamics reflect how these forces manifest in trade flows, price formation, and competitive positioning.

In Nigeria, aquaculture's rise is rooted in growing domestic demand for affordable and culturally acceptable protein sources. With capture fisheries unable to meet consumption needs, aquaculture has become a strategic component of the national food supply (Akinrotimi, Abu & Aranyo, 2011) [6]. Demand growth is further amplified by rapid urbanisation and rising incomes, which expand the customer base beyond subsistence consumers to include middle-income households willing to pay for higher-quality farmed fish. However, Nigerian producers face persistent constraints in input markets, particularly in feed and fingerling supply, where limited domestic production and reliance on imports expose them to currency volatility and international commodity price shifts. This dependency raises production costs and reduces competitiveness, particularly against imported frozen fish, which remains prevalent in urban retail markets.

Across sub-Saharan Africa, similar economic patterns emerge. Kassam (2013) [39] notes that small-scale aquaculture simultaneously serves commercial and subsistence functions, providing cash income and direct food supply to households. This dual role buffers producers from localised price shocks but is undermined by fragmented value chains, poor storage infrastructure, and limited access to real-time market information. Many producers are forced to sell at farm-gate prices due to inadequate transport networks, particularly in rural areas. These market inefficiencies not only constrain profitability but also dampen incentives for investment in productivity-enhancing technologies.

Globally, the aquaculture sector is increasingly tied to international market signals. Tveteras *et al*. (2012) [57] highlight the FAO Fish Price Index as a key measure of how global seafood markets influence national industries. Export-oriented aquaculture producers in developing nations—particularly in Asia and Latin America—have benefitted from rising prices for high-value species, generating foreign exchange and spurring domestic investment. However, such reliance on global markets introduces vulnerability to exogenous shocks, including disease outbreaks, abrupt trade policy changes, and shifts in consumer preferences in importing countries. For example, a sudden ban in a major export market can lead to oversupply domestically, depressing prices and threatening livelihoods.

Inland aquaculture in Asia provides useful comparative insights for African and Latin American contexts. Belton and Little (2011) [8] observe that the most successful systems are those where immanent (market-driven) development is complemented by interventionist policies, such as infrastructure investment, credit provision, and extension services. This hybrid model has facilitated the rapid growth of competitive aquaculture clusters that integrate production with processing and distribution, allowing farmers to capture more value. In contrast, in many African contexts, insufficient public investment and weak private sector linkages leave farmers isolated from higher-value markets.

Input market efficiency is a critical determinant of competitiveness. Feed accounts for 50–70% of operating costs in intensive and semi-intensive systems, making its price and quality pivotal economic drivers (FAO, 2020). In developing countries, feed industries are often underdeveloped, and imported feed is priced beyond the reach of many smallholders. This cost pressure incentivises the use of on-farm or locally mixed feeds, which may be nutritionally imbalanced, affecting growth rates and feed conversion efficiency. Naylor *et al*. (2021) [43] emphasise the need for innovation in alternative feed ingredients—such as plant proteins, insects, and microbial biomass—to reduce dependence on fishmeal and fish oil while maintaining productivity.

Market access is also shaped by consumer preferences, which differ markedly between domestic and export markets. Domestic markets often prioritise freshness and whole fish, while export markets may demand fillets, value-added products, and strict compliance with safety and traceability standards (FAO, 2020). Meeting these diverse requirements requires investment in processing capacity, quality assurance systems, and cold chain logistics. In Nigeria, where cold storage facilities remain scarce, producers targeting urban supermarkets must arrange costly private logistics, further eroding profit margins (Akinrotimi, Abu & Aranyo, 2011) [6].

Another significant driver is policy support, which can either stimulate or inhibit sector growth. Targeted subsidies for feed production, preferential credit for aquaculture enterprises, and investment in market infrastructure can enhance competitiveness. Conversely, policy inconsistency and weak enforcement of quality standards can undermine market confidence. Kassam (2013) [39] stresses that in sub-

Saharan Africa, policy frameworks often prioritise production expansion without parallel investment in market systems, leading to periodic gluts and price collapses.

Finally, the sector is increasingly influenced by sustainability concerns in both domestic and international markets. As Naylor *et al*. (2021) [43] observe, consumer awareness of environmental and social issues in aquaculture is growing, and certifications such as the Aquaculture Stewardship Council (ASC) are gaining traction. While compliance can open premium markets, the cost and complexity of certification remain prohibitive for many small-scale producers. Without collective approaches—such as group certification or cooperative marketing—many producers risk exclusion from the most lucrative market segments.

2.4 Institutional and Policy Frameworks

The institutional and policy frameworks governing aquaculture form the structural backbone upon which sectoral growth, sustainability, and equitable benefits depend. In developing nations, where aquaculture often emerges as both an economic opportunity and a strategy for food security, the quality, coherence, and enforcement of these frameworks can determine whether the sector evolves sustainably and inclusively or succumbs to environmental degradation and socio-economic inequities.

Institutional arrangements in aquaculture encompass a broad array of governmental and non-governmental entities, including ministries of fisheries or agriculture, environmental protection agencies, research institutions, and producer associations. The degree of coordination among these actors is pivotal. FAO (2020) underscores that fragmented institutional mandates often result in policy incoherence, overlapping regulations, and inconsistent enforcement—issues particularly acute in many low- and middle-income countries. Effective governance requires not only clear legislative frameworks but also robust inter-agency collaboration to ensure that environmental safeguards, market development policies, and rural livelihood objectives are pursued in an integrated fashion.

In Nigeria, the aquaculture sector is regulated primarily under the purview of the Federal Ministry of Agriculture and Rural Development, supported by state-level agencies. While policy documents acknowledge aquaculture's potential to enhance food security and reduce poverty, implementation challenges persist. Akinrotimi, Abu, and Aranyo (2011) [6] highlight deficiencies in environmental oversight, noting that while sustainable farming guidelines exist on paper, enforcement is limited by inadequate technical capacity and budgetary constraints. Furthermore, weak institutional support for extension services hampers the transfer of sustainable farming practices to small-scale farmers, who make up the majority of producers.

The experience of other African nations provides both cautionary and instructive examples. Kassam (2013) [39] emphasises that in much of sub-Saharan Africa, policy frameworks have historically prioritised production growth over sustainability, with limited attention to market development, environmental protection, or equitable access to resources. This production-centric approach can yield short-term gains in output but risks long-term sectoral instability. In contrast, countries that have adopted multi-stakeholder governance models, involving producer cooperatives, NGOs, and research bodies in policy formulation, have been more successful in aligning production goals with environmental and social safeguards.

Globally, the importance of policy frameworks in shaping aquaculture trajectories is well established. Brugère and Ridler (2004) [15] argue that accurate long-term production forecasting requires consideration of not only biological and technical factors but also the enabling policy environment, including trade regulations, subsidies, and investment in infrastructure. The global trend towards integrating aquaculture into broader blue economy strategies reflects a growing recognition that the sector's governance must be embedded within holistic frameworks addressing ecosystem health, climate resilience, and socio-economic development.

Market access policies are another critical dimension of aquaculture governance. Belton, Bush, and Little (2018) [9] note that policies influencing the distribution and affordability of farmed fish can profoundly affect food security outcomes in the Global South. For example, trade policies that favour exports of high-value species may stimulate foreign exchange earnings but risk diverting affordable fish away from domestic consumers, exacerbating nutritional inequalities. This tension is particularly relevant in developing countries where domestic markets are highly sensitive to price changes and where farmed fish often constitute the most accessible source of animal protein for low-income households.

At the international level, compliance with sanitary and phytosanitary standards, as well as environmental certification schemes, increasingly shapes aquaculture market dynamics. FAO (2020) points out that while these frameworks can incentivise sustainable practices and open access to premium markets, they can also create barriers for small-scale producers who lack the resources to meet stringent requirements. Addressing this requires policies that facilitate capacity building, such as cooperative certification schemes, technical training, and subsidies for compliance infrastructure.

Climate change adaptation is an emerging area where institutional and policy frameworks must evolve rapidly. Many developing countries have yet to integrate aquaculture explicitly into national adaptation plans, despite the sector's vulnerability to temperature fluctuations, extreme weather events, and changes in water availability (FAO, 2020). Strengthening adaptive capacity will require not only targeted research and technology dissemination but also flexible policy instruments that allow producers to respond to rapidly changing environmental and market conditions.

2.5 Capacity Building and Education

Capacity building and education are pivotal components in advancing sustainable aquaculture practices, particularly in developing nations where technical expertise, access to updated knowledge, and institutional support structures are often limited. The successful transformation of aquaculture from subsistence or small-scale production to a robust contributor to food security, economic growth, and environmental sustainability depends largely on the sector's human capital. The presence of well-trained farmers, effective extension services, and responsive educational institutions determines whether innovations in technology and management can be implemented effectively at the grassroots level.

In Nigeria, aquaculture capacity building has been a focal point of national strategies to boost fish production and reduce reliance on imports. Akinrotimi, Abu, and Aranyo (2011) [6] emphasise that despite Nigeria's vast aquaculture potential, many farmers lack the technical skills required to manage farms efficiently, particularly with regard to water quality control, feed management, and disease prevention. Limited access to formal aquaculture training programmes compounds this challenge, leaving many producers reliant on informal knowledge transfer, which may perpetuate unsustainable practices. Public-sector extension services, once more robust, have weakened due to funding constraints, necessitating the involvement of universities, research institutions, and non-governmental organisations in delivering targeted training and demonstration projects.

Across sub-Saharan Africa, similar capacity gaps are evident. Kassam(2013) [39] notes that aquaculture expansion is often pursued without adequate investment in human resource development, resulting in low productivity and poor adoption of best practices. They argue that capacity building should be viewed not merely as skills training but as an integrated process that includes farmer education, institutional strengthening, and the development of supportive policies. Such an approach can help align technical training with broader socio-economic goals, ensuring that small-scale producers can participate competitively in both local and regional markets. Furthermore, knowledge dissemination needs to be tailored to local conditions, taking into account variations in species, farming systems, and environmental constraints.

Globally, capacity building in aquaculture has been increasingly recognised as a central pillar of sustainable development in the sector. FAO (2020) highlights that capacity building encompasses a wide spectrum of activities, from vocational training and farmer field schools to advanced university degrees and applied research partnerships. The most effective programmes are participatory, enabling farmers to share indigenous knowledge while integrating new scientific techniques. This co-learning approach enhances the relevance and uptake of new methods, particularly in contexts where traditional practices have been honed over generations to match specific ecological and cultural conditions.

Education in aquaculture must also address cross-cutting issues such as gender equity and social inclusion. Brugère, McAndrew, and Bulcock (2001) [16] point out that aquaculture training and development initiatives often fail to reach women, despite their substantial involvement in post-harvest handling, marketing, and even farm management in many developing countries. Structural barriers, including limited access to land, credit, and formal training opportunities, can marginalise women from the economic benefits of aquaculture. Addressing this requires deliberate inclusion strategies, such as scheduling training sessions at times compatible with household responsibilities, providing childcare facilities, and actively recruiting female extension officers.

Capacity building is equally vital for promoting integrated and environmentally sustainable practices. Ahmed and Garnett (2011) [3] illustrate how training farmers in integrated rice–fish systems in Bangladesh has enabled them to enhance both rice yields and fish production while reducing reliance on chemical inputs. Such systems, which optimise the ecological interactions between crops and aquaculture species, require a sound understanding of both agricultural and aquacultural principles. Education that bridges these domains can foster diversified farming systems that are more resilient to market volatility and climate change.

One of the critical enablers of effective capacity building is the establishment of partnerships between stakeholders. Public-private partnerships, collaborations between research institutions and farmer cooperatives, and regional training networks can all play transformative roles. FAO (2020) recommends that governments in developing countries prioritise investment in national aquaculture research and training centres, ensuring they are equipped to provide not only technical instruction but also guidance on business planning, market access, and compliance with quality and safety standards. This is particularly important in a global market increasingly shaped by certification schemes and traceability requirements.

In the context of rapidly changing climatic and market conditions, ongoing education—rather than one-time training—is essential. The challenges faced by aquaculture producers, from emerging diseases to input price volatility, require adaptive management strategies. Continuous professional development for farmers and extension agents can ensure they remain informed about technological innovations, regulatory changes, and shifting market demands. Digital learning platforms and mobile-based advisory services are emerging tools that can extend the reach of capacity-building programmes, especially in rural areas with limited access to physical training facilities.

2.6 Innovations and Technological Interventions

The evolution of aquaculture in developing nations has been profoundly shaped by innovations and technological interventions that seek to address the sector's dual challenges of productivity enhancement and environmental sustainability. As global demand for aquatic products continues to rise, innovation has become indispensable in enabling aquaculture to meet production targets while maintaining ecological integrity and contributing to socio-economic development. These innovations span breeding, feed formulation, farm management, disease control, waste treatment, and market integration, each offering pathways for transformative change.

In Nigeria, technological advancements have primarily targeted improvements in hatchery operations, feed quality, and farm management systems to enhance production efficiency. According to Issa, Aderinoye-AbdulWahab, and Kagbu (2022) [37], local innovations—such as producing affordable extruded feeds from locally available ingredients—have been instrumental in reducing dependence on costly imports and improving profitability for small-scale farmers. Notable progress has also been made in breeding programmes for species like Clarias gariepinus and Oreochromis niloticus. However, the uptake of advanced hatchery technologies remains inconsistent, largely due to financial limitations and insufficient technical capacity. Additionally, the use of digital solutions, including mobile-based advisory platforms, is gaining traction as a cost-effective way to share best practices with rural farmers, facilitating real-time responses to challenges in water quality management and disease control.

Across sub-Saharan Africa, innovations have similarly aimed at bridging productivity gaps while safeguarding environmental resources. Kassam (2013) [39] highlights the introduction of integrated aquaculture–agriculture systems, where fish farming is combined with crop cultivation to optimise nutrient cycling and water use efficiency. In countries like Uganda and Zambia, the deployment of improved cage culture designs in lakes and reservoirs has facilitated expansion in areas with limited access to land and freshwater, although these technologies require careful regulation to mitigate nutrient loading and protect water quality. Furthermore, regional research collaborations have accelerated the dissemination of improved genetic strains of tilapia and catfish, enabling farmers to achieve higher growth rates and better feed conversion ratios.

Globally, technological innovation in aquaculture has advanced rapidly over the last two decades, driven by the need to improve efficiency, environmental performance, and product quality. FAO (2020) documents the growing uptake of Recirculating Aquaculture Systems (RAS), which allow intensive fish production in controlled environments with minimal water use and reduced risk of disease transmission from the external environment. While capital-intensive, RAS technology offers particular promise in urban and peri-urban contexts where land and water resources are scarce. Complementary advances in biofloc technology—where beneficial microbial communities recycle waste into additional feed—have enabled significant reductions in feed costs and environmental impacts, making them attractive for adoption in small- to medium-scale operations.

The value of research, technological development, and innovation in aquaculture is well established. Bostock *et al*. (2010) emphasise that innovations in feed formulation, breeding, and disease diagnostics have delivered substantial economic and environmental benefits. For example, the replacement of fishmeal with plant-based proteins and novel ingredients such as insect meal has alleviated pressure on wild fish stocks, while selective breeding programmes have yielded disease-resistant strains that reduce dependency on antibiotics. Such innovations align with global sustainability objectives by minimising environmental footprints and enhancing the resilience of production systems.

Technological interventions are not limited to production; they also encompass post-harvest handling and market integration. Cold chain innovations, value-added processing, and blockchain-based traceability systems are increasingly important in connecting producers in developing nations to high-value export markets. Troell *et al*. (2014) [56] argue that by enhancing the transparency and efficiency of supply chains, these technologies can strengthen aquaculture's role in global food systems. However, they caution that without equitable access to these technologies, benefits may be disproportionately captured by larger, capitalised enterprises, potentially marginalising small-scale producers.

Adoption of innovations in developing nations is influenced by a complex interplay of economic, institutional, and social factors. In many cases, high upfront costs, limited access to credit, and inadequate technical training hinder the diffusion of advanced technologies. FAO (2020) underscores the importance of coupling technological interventions with capacity building, extension services, and supportive policy frameworks. Public–private partnerships have proven effective in scaling up innovations, with governments, research institutions, and private firms collaborating to adapt technologies to local conditions and ensure affordability for smallholders.

The sustainability consequences of technological interventions are significant. Although innovations such as RAS, biofloc systems, and integrated multi-trophic aquaculture provide notable environmental advantages, their enduring success relies on careful alignment with ecological, economic, and cultural conditions. Issa, Aderinoye-AbdulWahab, and Kagbu (2022) [37] note that in Nigeria, technologies misaligned with farmers' resource capabilities and prevailing market realities are often abandoned after initial adoption. This reinforces the importance of participatory innovation processes in which end-users are actively engaged in the design, testing, and scaling of new technologies.

2.7 Monitoring, Certification, and Traceability Systems

Monitoring, certification, and traceability systems have become indispensable mechanisms for safeguarding environmental sustainability, ensuring food safety, and enhancing the market competitiveness of aquaculture products. In an era defined by globalised seafood trade, these systems are no longer discretionary; they represent fundamental prerequisites for access to premium markets and for sustaining consumer confidence in both domestic and international supply chains. Their relevance is particularly pronounced in developing nations, where aquaculture is positioned not only as a key contributor to dietary protein supply but also as a driver of economic diversification, rural development, and foreign exchange earnings.

Monitoring systems in aquaculture perform the dual role of protecting environmental integrity and verifying compliance with regulatory and market requirements. Effective monitoring ensures that aquaculture operations adhere to water quality standards, employ appropriate feed management practices, and maintain biosecurity measures to prevent disease outbreaks. However, in Nigeria, regulatory oversight is significantly hampered by institutional weaknesses and resource limitations. Olaoye *et al*. (2016) [44] observed that while a considerable proportion of fish farmers in Ogun State possessed an awareness of quality and safety regulations, practical compliance remained inconsistent. This non-compliance was attributed to a lack of adequate monitoring infrastructure, limited access to training, and the financial burden associated with implementing regulatory requirements. Such gaps between legislative intent and on-the-ground practice illustrate the urgent need for investment in modern surveillance systems, accredited laboratory facilities, and digital monitoring platforms capable of delivering real-time data on critical parameters such as dissolved oxygen levels, feed conversion efficiency, and harvesting protocols.

Comparable challenges are evident across other African aquaculture-producing nations, yet some countries have begun to implement proactive policy-driven measures to bridge these gaps. In Kenya, for instance, the national aquaculture development strategy explicitly prioritises the integration of monitoring and quality assurance into both domestic and export-oriented production (Charo-Karisa & Gichuri, 2010). Key initiatives have included capacity-building programmes for fisheries officers, the introduction of standardised inspection protocols for aquaculture facilities, and the design of certification frameworks harmonised with international trade requirements. While these measures demonstrate an institutional commitment to quality control, their sustainability depends on consistent funding, specialised technical training, and active collaboration between government agencies, producer cooperatives, and private sector value-chain actors.

Certification schemes have emerged as one of the most visible and influential instruments for quality assurance in global aquaculture. According to Bush *et al*. (2013) [19], internationally recognised schemes such as the Aquaculture Stewardship Council (ASC), Best Aquaculture Practices (BAP), and Global G.A.P. increasingly form part of procurement requirements for major retailers and are valued by consumers in Europe, North America, and parts of Asia. These certification programmes evaluate compliance across multiple dimensions, including environmental stewardship, social responsibility, and adherence to stringent food safety protocols. While the attainment of certification can provide producers with access to lucrative export markets and strengthen brand reputation, it also introduces substantial challenges for small-scale producers in developing countries. The high cost of certification audits, the administrative complexity of record-keeping, and the infrastructural investments often required to meet standards present formidable barriers to entry. Without targeted support, there is a risk that certification schemes could exacerbate inequalities within the sector, concentrating market access among larger, better-resourced operators.

Complementing certification, traceability systems have assumed a pivotal role in enhancing transparency along aquaculture supply chains. These systems enable stakeholders to track products from the point of origin to the final consumer, thereby providing assurances regarding production practices, geographical origin, and compliance with established standards. The Food and Agriculture Organization (FAO, 2020) underscores the dual importance of traceability in fulfilling import regulations and in facilitating the rapid containment of disease outbreaks or contamination incidents. Recent advancements in digital technologies, including blockchain-based traceability platforms, offer promising opportunities to develop secure, low-cost, and tamper-proof systems. However, as Ponte, Gereffi, and Raj-Reichert (2019) [34] caution, the integration of such technologies into global value chains requires careful governance to ensure equitable distribution of costs and benefits. Without inclusive governance structures, traceability systems risk reinforcing power asymmetries, disproportionately favouring vertically integrated firms with substantial capital reserves over smaller, independent producers.

The alignment of monitoring, certification, and traceability systems with broader sustainability goals has increasingly entered the policy discourse. FAO (2020) highlights the potential for these mechanisms to act as market-based incentives for the adoption of responsible aquaculture practices, thereby promoting environmental protection, social equity, and product quality simultaneously. Yet, the transferability of these systems into developing-country contexts requires significant adaptation. Simplifying certification requirements—without undermining the credibility of the standards—can help reduce compliance costs. Group certification models, often facilitated through cooperatives, provide another pathway for small-scale producers to share resources, distribute certification costs, and collectively access high-value markets. Similarly, embedding traceability systems within existing market structures, rather than creating entirely new and parallel frameworks, can reduce duplication and improve cost-efficiency.

Capacity building forms the cornerstone of any successful implementation of monitoring, certification, and traceability systems. Olaoye *et al*. (2016) [44] emphasise that enhancing farmer proficiency in areas such as quality control, meticulous record-keeping, and standard compliance is essential to closing the gap between regulatory awareness and practical adherence. Structured training programmes, particularly those employing participatory learning methods, can empower farmers to internalise and apply these requirements effectively. In Kenya, Charo-Karisa and Gichuri (2010) report that collaborations between government bodies and international development agencies have yielded promising results through "certification readiness" initiatives, which provide targeted technical support to farmers, enabling them to meet audit requirements at reduced initial costs. Such initiatives illustrate the potential for replicable models that could be adapted to other aquaculture-producing nations within Africa and beyond.

The market implications of robust and well-integrated monitoring, certification, and traceability systems are significant. For export-oriented aquaculture sectors, compliance with these mechanisms is a non-negotiable condition for maintaining and expanding market access, particularly in regions where consumer awareness and regulatory scrutiny are high. In domestic markets, these systems can serve as powerful differentiators, distinguishing responsibly farmed products from less regulated wild-caught alternatives and enabling producers to command premium prices. Nonetheless, as Bush *et al*. (2013) [19] caution, the sustainability and inclusivity benefits of these systems are not guaranteed. Without rigorous governance and enforcement, certification risks being reduced to a marketing label devoid of substantive environmental or social impact, while traceability may become a gatekeeping tool that entrenches the marginalisation of small-scale producers.

2.8 Climate Change and Aquaculture Resilience

Climate change presents a profound and multidimensional challenge to aquaculture systems worldwide, with implications that extend beyond production efficiency to affect economic viability, food security, and the ecological sustainability of farming practices. Its impacts on aquaculture are mediated through both gradual environmental shifts—such as increasing water temperatures, ocean acidification, and altered precipitation patterns—and the heightened frequency of extreme events, including floods, droughts, and storms (Barange *et al*., 2018) [7]. For developing nations, where aquaculture is often pursued as a climate-resilient livelihood strategy, the paradox lies in the sector's simultaneous vulnerability to and potential role in climate change adaptation.

In Nigeria, climate change is already influencing aquaculture productivity and operational stability. Akinrotimi, Uka, and Opara (2019) identify erratic rainfall patterns, increased incidence of flooding, and prolonged dry seasons as major stressors affecting pond aquaculture. Elevated water temperatures can accelerate fish metabolism, leading to higher feed conversion rates, yet they also increase susceptibility to diseases and reduce dissolved oxygen levels, which may trigger mass mortalities. Such environmental variability undermines production predictability and profitability, particularly for smallholder farmers who lack access to adaptive infrastructure such as aeration systems, water storage facilities, or controlled-environment technologies.

Across Africa, the risks posed by climate change to aquaculture are compounded by the sector's dependence on ecosystem services that are themselves under stress. Charo-Karisa, Githukia, and Opiyo (2018) [46] note that aquaculture in the region often relies on inland water bodies whose hydrological regimes are highly sensitive to climate variability. Drought events can lead to reduced water availability, while flooding can damage infrastructure, introduce pollutants, and facilitate the spread of pathogens. In coastal areas, sea-level rise and saltwater intrusion threaten brackish-water aquaculture systems, with cascading effects on species composition and yield. These vulnerabilities are not evenly distributed; they disproportionately affect small-scale producers who lack both the capital and institutional support to implement effective adaptive measures.

At the global scale, climate change is expected to shift the geographical distribution and productivity potential of aquaculture. Froehlich, Gentry, and Halpern (2018) [32] project that some temperate regions may experience increased production potential due to longer growing seasons and improved feed conversion ratios, whereas tropical regions—where aquaculture is often most critical for food security—are likely to face declines due to thermal stress and increased disease prevalence. The spatial redistribution of aquaculture potential under climate change underscores the urgency for proactive adaptation strategies, particularly in developing nations where the scope for relocation of production facilities is constrained by socio-economic and environmental factors.

Adaptation in aquaculture encompasses both technological and management interventions designed to increase system resilience. Globally, measures such as selective breeding for heat- and disease-tolerant strains, the adoption of recirculating aquaculture systems (RAS), and the integration of multi-trophic aquaculture have shown promise in reducing climate-related risks (De Silva & Soto, 2009) [24]. In Nigeria, adaptive innovations have encompassed the introduction of water recirculation technologies in urban and peri-urban aquaculture, alongside the diversification of cultured species to include those more resilient to variable water quality conditions (Benjamin, Ola & Buchenrieder, 2022) [10]. (Akinrotimi, Uka & Opara, 2019). However, these measures remain limited in scale due to cost barriers and the lack of technical extension services that can facilitate adoption.

Policy and governance play a critical role in shaping the adaptive capacity of aquaculture systems. Barange *et al.* (2018) [7] emphasise that national adaptation plans should explicitly incorporate aquaculture as both a vulnerable sector and a potential contributor to climate change mitigation through sustainable intensification and ecosystem restoration. In Africa, regional cooperation through initiatives such as the African Union's Blue Economy Strategy has created opportunities for sharing knowledge, mobilising resources, and developing climate-smart aquaculture guidelines. However, the translation of such frameworks into localised action is often slow, hindered by fragmented institutional responsibilities and competing development priorities.

Mitigation measures, while less frequently discussed in aquaculture than adaptation, are increasingly relevant given the sector's own environmental footprint. De Silva and Soto (2009) [24] note that aquaculture contributes to greenhouse gas emissions through feed production, energy use, and methane release from ponds. Reducing these emissions requires innovations such as optimised feed formulations that reduce reliance on high-carbon inputs, energy-efficient pumping and aeration systems, and the integration of carbon-sequestering species such as seaweeds into production systems. Charo-Karisa, Githukia, and Opiyo (2018). Additionally, integrated aquaculture–agriculture systems hold significant potential to recycle nutrients, improve water-use efficiency, and enhance climate resilience at the landscape level.

Capacity building remains essential for enabling effective adaptation and mitigation. Training farmers in climate risk assessment, adaptive farm management, and the use of early-warning systems for extreme weather can significantly reduce vulnerability. This requires coordinated action among governments, research institutions, and the private sector to ensure that climate-smart technologies are accessible, affordable, and culturally appropriate. FAO-led initiatives, as documented by Barange *et al.* (2018) [7], have demonstrated the value of participatory approaches in which farmers are actively involved in identifying risks and testing adaptive solutions, thereby enhancing both uptake and long-term sustainability.

Climate change also introduces complex market dynamics that interact with aquaculture resilience. Supply disruptions caused by extreme events can lead to price volatility, affecting both producer incomes and consumer access to affordable fish. In export-oriented sectors, climate-related production variability can undermine the reliability of supply chains, potentially eroding market relationships. Froehlich, Gentry, and Halpern (2018) [32] argue that resilience planning must therefore consider not only biophysical adaptation but also strategies for market and supply chain stability, including diversification of product lines, market destinations, and input sources.

2.9 Gender and Equity in Sustainable Aquaculture

Gender and equity considerations in sustainable aquaculture have gained increasing attention in recent years, reflecting a broader recognition that social inclusivity is integral to the sector's long-term viability. While aquaculture is often lauded for its potential to improve food security and rural livelihoods, the distribution of benefits within communities is rarely equitable. Structural inequalities, particularly those based on gender, shape access to resources, decision-making power, and income opportunities. Without deliberate policy and institutional measures, aquaculture development risks reinforcing existing disparities rather than promoting inclusive growth.

In Nigeria, gendered divisions of labour are deeply embedded in aquaculture value chains. Olaoye *et al.* (2012) [45] note that women are predominantly involved in post-harvest processing, marketing, and retailing of fish, while men are more likely to control pond ownership, input procurement, and primary production activities. This gendered distribution of roles limits women's access to the more lucrative segments of the aquaculture value chain and restricts their influence in decision-making forums that determine investment priorities and resource allocation.

Furthermore, cultural norms and unequal access to land, credit, and training compound these disadvantages, perpetuating cycles of economic marginalisation for women despite their essential contributions to the sector.

Similar patterns are evident across other African aquaculture contexts. In Kenya, Charo-Karisa and Gichuri (2010) highlight that women play critical roles in fish farming cooperatives and marketing networks, yet they remain underrepresented in leadership positions. Even where women own ponds or participate in production, their operations are often smaller in scale and less mechanised, constraining productivity and profitability. These disparities stem not only from material resource gaps but also from systemic biases in extension services, which have historically targeted male farmers, limiting women's access to technical knowledge and innovation.

From a global perspective, gender disparities in aquaculture are not limited to developing regions but manifest differently across cultural and economic contexts. Kruijssen, McDougall, and van Asseldonk (2018) [40] stress that women's contributions are frequently underreported or rendered invisible in official statistics, particularly in small-scale operations and informal market activities. This invisibility has significant policy implications: without accurate data on women's participation, interventions risk overlooking the needs and priorities of half the workforce. Addressing this requires a more nuanced understanding of gendered roles along the value chain, from hatcheries and grow-out facilities to processing plants and distribution channels.

Weeratunge, Snyder, and Choo (2010) [58] propose that gender analysis in aquaculture should move beyond simplistic categorizations of male versus female roles to consider intersectional factors such as age, socio-economic status, and marital status, all of which influence access to resources and bargaining power. For instance, young unmarried women may face additional barriers to securing land or credit, while widows might experience both increased economic responsibility and social vulnerability. By incorporating these intersectional dimensions into aquaculture development planning, interventions can be better tailored to address the diverse realities within farming communities.

Institutional and policy frameworks are critical in addressing gender and equity gaps in aquaculture. FAO (2021) [30] emphasises that integrating gender considerations into national aquaculture policies requires more than rhetorical commitments—it demands concrete measures such as gender-responsive budgeting, targeted training programmes, and quotas for women's representation in governance bodies. Capacity-building initiatives tailored to women's needs, including flexible training schedules and on-site demonstrations, can help overcome barriers related to mobility, domestic responsibilities, and literacy levels. Additionally, facilitating women's access to collective action through cooperatives and producer associations can enhance their bargaining power in both input and output markets.

Equity in aquaculture also encompasses the fair distribution of benefits among other marginalised groups, including youth, indigenous communities, and migrant workers. Many of these groups encounter overlapping forms of exclusion that limit their participation in the sector's growth opportunities. FAO (2021) [30] notes that promoting decent work conditions, ensuring occupational safety, and providing social protection measures are essential components of equitable aquaculture development. Without such protections, the sector's expansion can exacerbate socio-economic vulnerabilities, particularly in contexts where informal labour dominates.

Market-based interventions have the potential to promote greater gender equity when designed thoughtfully. Certification schemes, for example, can incorporate gender criteria into their standards, incentivising farms to adopt inclusive employment practices and equitable benefit-sharing mechanisms. However, as Kruijssen, McDougall, and van Asseldonk (2018) [40] caution, these initiatives must be accompanied by robust monitoring to ensure that gender commitments translate into tangible outcomes rather than symbolic compliance.

2.9.1 Indigenous Knowledge and Cultural Dimensions

Indigenous knowledge and cultural practices represent critical, yet often underutilised, dimensions of sustainable aquaculture. These systems of knowledge, developed over generations, integrate local ecological understanding, resource management strategies, and socio-cultural norms, providing context-specific solutions that modern aquaculture models sometimes overlook. In the pursuit of sustainable aquaculture in developing nations, recognising and integrating such indigenous knowledge into formal governance and technological innovation can enhance both ecological resilience and community acceptance.

In Nigeria, traditional aquaculture practices—such as seasonal fish trapping, floodplain pond culture, and the communal stewardship of natural water bodies—have long supported rural livelihoods. These systems are intrinsically adaptive, aligning with seasonal hydrological regimes and the dynamics of local biodiversity, much like the broader ecological patterns described by Rolls *et al*. (2018) [52]. They are frequently embedded within community governance structures that determine access, regulate harvest timing, and guide species selection, thereby fostering sustainability without reliance on externally imposed controls. However, the growing shift towards intensive aquaculture technologies, while capable of delivering higher yields, has in some cases displaced these traditional methods and the socio-cultural frameworks that underpin them.

Across Africa, indigenous aquaculture knowledge continues to shape decisions on species selection, breeding, and husbandry practices. In Ghana, for example, farmers utilise traditional methods for breeding Clariasgariepinus, including the use of locally made hapa nets and the timing of spawning to coincide with rainfall patterns—an approach consistent with the biological insights into the species reported by Dogah (2020) [26]. These techniques reduce dependence on expensive hatchery facilities and chemical inputs, making them well suited to low-capital farming systems. Moreover, they embody a deep familiarity with local ecological conditions, offering valuable guidance for developing adaptive strategies in the face of climate variability.

Globally, the value of traditional ecological knowledge (TEK) in resource management has been well-documented. Berkes, Colding, and Folke (2000) [11] argue that TEK functions as a form of adaptive management, grounded in continuous observation, feedback, and innovation. In aquaculture, this translates into practices such as polyculture, integrated farming, and water management systems that balance productivity with ecosystem health. These locally evolved approaches often align with principles of ecological aquaculture, making them highly relevant to contemporary sustainability goals.

Cultural dimensions also play a crucial role in determining the acceptance and success of aquaculture interventions. The FAO (2015) [29] emphasises that small-scale fisheries and aquaculture initiatives must respect cultural heritage, local governance systems, and traditional rights to ensure legitimacy and equitable benefit-sharing. Disregarding these dimensions can lead to community resistance, reduced participation, and ultimately the failure of development projects. For instance, species that are culturally valued or taboo can influence production choices, while traditional tenure systems may dictate access to aquaculture sites.

Community-based management models that integrate indigenous knowledge have proven effective in other parts of the world. Johannes (2002) [38] documents the renaissance of community-based marine resource management in Oceania, where local customs, seasonal taboos, and traditional enforcement mechanisms have been revitalised to address modern resource challenges. While the ecological and socio-political contexts differ, similar approaches could be adapted for inland and coastal aquaculture in Africa, ensuring that management frameworks resonate with local cultural norms.

3. Conclusion

This study aimed to critically examine sustainable aquaculture practices in developing countries, focusing on how economic viability can be balanced with environmental integrity. The goals included exploring the conceptual foundations of sustainable aquaculture, assessing its socio-economic importance, identifying environmental considerations, understanding institutional and policy frameworks, examining the role of capacity building and education, highlighting technological innovations, and evaluating the roles of monitoring, certification, traceability, climate resilience, gender equity, and indigenous knowledge systems. Through a systematic review of scholarly literature and case examples from Nigeria, other African countries, and global experiences, the study successfully achieved these objectives.

Key findings show that sustainable aquaculture must be viewed as an integrated system, balancing ecological responsibility with social and economic inclusion. Economically, the sector's growth is fueled by rising domestic demand, export prospects, and technological progress, but it faces challenges like input costs, infrastructure gaps, and market inefficiencies. Socially, aquaculture offers vital livelihood opportunities and improves food security, but benefits are not shared equally, especially among women and marginalized groups, highlighting the need for targeted interventions focused on equity.

Environmentally, the sustainability of aquaculture depends on effective management of nutrient loading, habitat protection, and adaptive responses to climate change. Policy and institutional frameworks are crucial, with evidence showing that coherent, participatory governance improves compliance with environmental and market standards. Building capacity, education, and the adoption of technological innovations—such as recirculating aquaculture systems, biofloc technology, and integrated multi-trophic systems—are key to increasing productivity while reducing ecological footprints. Additionally, monitoring, certification, and traceability systems are vital for ensuring product quality, market competitiveness, and consumer trust.

The study concludes that achieving truly sustainable aquaculture in developing nations requires a multidimensional strategy that unites economic efficiency, environmental responsibility, and social justice. Recommendations include strengthening policy coherence across sectors, expanding training and extension services, incentivising environmentally friendly innovations, supporting smallholders in achieving certification, and embedding indigenous and gender-responsive approaches into formal aquaculture planning. By implementing these measures, developing nations can position aquaculture not only as a key pillar of food security but also as a model for inclusive, climate-resilient, and environmentally sound development. This integrated approach aligns with global sustainability goals and ensures that the sector contributes meaningfully to both present and future societal needs.

4. References

1. Adeosun OM, Olaoye OJ, Ojebiyi WG, Agarawu OL, Adeosun FI. Profitability Analysis of Catfish Production in Odogbolu Local Government Area of Ogun State, Nigeria. Nigerian Journal of Agriculture and Agricultural Technology. 2024; 4(2):187-202.
2. Ahmed M, Lorica MH. Improving developing country food security through aquaculture development-lessons from Asia. Food Policy. 2002; 27(2):125-141. Doi: https://doi.org/10.1016/S0306-9192(02)00007-6
3. Ahmed N, Garnett ST. Integrated rice-fish farming in Bangladesh: Meeting the challenges of food security. Food Security. 2011; 3(1):81-92. Doi: https://doi.org/10.1007/s12571-011-0113-8
4. Ahmed N, Thompson S, Glaser M. Integrated mangrove-shrimp cultivation: Potential for blue carbon sequestration. Ambio. 2018; 47(4):441-452. Doi: https://doi.org/10.1007/s13280-017-0946-2
5. Ahmed N, Thompson S, Glaser M. Global aquaculture productivity, environmental sustainability, and climate change adaptability. Environmental Management. 2019; 63(2):159-172. Doi: https://doi.org/10.1007/s00267-018-1117-3
6. Akinrotimi OA, Abu OMG, Aranyo AA. Environmentally friendly aquaculture is key to sustainable fish farming development in Nigeria. Continental Journal of Fisheries and Aquatic Science. 2011; 5(2):17-31. Doi: http://hdl.handle.net/1834/24296
7. Barange M, Bahri T, Beveridge MC, Cochrane KL, Funge-Smith S, Poulain F. Impacts of climate change on fisheries and aquaculture. United Nations' Food and Agriculture Organization. 2018; 12(4):628-635.
8. Belton B, Little DC. Immanent and interventionist inland Asian aquaculture development and its outcomes. Development Policy Review. 2011; 29(4):459-484. Doi: https://doi.org/10.1111/j.1467-7679.2011.00539.x
9. Belton B, Bush SR, Little DC. Not just for the wealthy: Rethinking farmed fish consumption in the Global South. Global Food Security. 2018; 16:85-92. Doi: https://doi.org/10.1016/j.gfs.2017.10.005
10. Benjamin EO, Ola O, Buchenrieder GR. Feasibility

study of a small-scale recirculating aquaculture system for sustainable (Peri-) urban farming in Sub-Saharan Africa: A Nigerian Perspective. Land. 2022; 11(11):p2063. Doi: https://doi.org/10.3390/land11112063
11. Berkes F, Colding J, Folke C. Rediscovery of traditional ecological knowledge as adaptive management. Ecological Applications. 2000; 10(5):1251-1262. Doi: https://doi.org/10.1890/1051-0761(2000)010[1251:ROTEKA]2.0.CO;2
12. Bosma RH, Verdegem MC. Sustainable aquaculture in ponds: Principles, practices and limits. Livestock Science. 2011; 139(1-2):58-68. Doi: https://doi.org/10.1016/j.livsci.2011.03.017
13. Bostock J, Lane A, Hough C, Yamamoto K. An assessment of the economic contribution of EU aquaculture production and the influence of policies for its sustainable development. Aquaculture International. 2016; 24(3):699-733. Doi: https://doi.org/10.1007/s10499-016-9992-1
14. Boyd CE, D'Abramo LR, Glencross BD, Huyben DC, Juarez LM, Lockwood GS, *et al*. Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. Journal of the World Aquaculture Society. 2020; 51(3):578-633. Doi: https://doi.org/10.1111/jwas.12714
15. Brugère C, Ridler N. Global aquaculture outlook in the next decades: An analysis of national aquaculture production forecasts to 2030, 2004.
16. Brugère C, Mcandrew K, Bulcock P. Does cage aquaculture address gender goals in development? Results of a case study in Bangladesh. Aquaculture Economics & Management. 2001; 5(3-4):179-189. Doi: https://doi.org/10.1080/13657300109380286
17. Bunting SW. Principles of sustainable aquaculture: promoting social, economic, and environmental resilience. Routledge, 2024. Doi: https://doi.org/10.4324/9781003342823
18. Bunting SW. Principles of sustainable aquaculture: promoting social, economic, and environmental resilience. Routledge, 2024. Doi: https://www.taylorfrancis.com/books/mono/10.4324/9781003342823
19. Bush SR, Belton B, Hall D, Vandergeest P, Murray FJ, Ponte S, *et al*. Certify sustainable aquaculture? Science. 2013; 341(6150):1067-1068. Doi: https://doi.org/10.1126/science.1237314
20. Campanati C, Willer D, Schubert J, Aldridge DC. Sustainable intensification of aquaculture through nutrient recycling and circular economies: More fish, less waste, blue growth. Reviews in Fisheries Science & Aquaculture. 2022; 30(2):143-169. Doi: https://doi.org/10.1080/23308249.2021.1897520
21. Charo-Karisa H, Gichuri M. Overview of the fish farming enterprise and the aquaculture development strategy 2010-2015. Nairobi: Aquaculture Development Working Group, Ministry of Fisheries Development, 2010. https://koreascience.kr/article
22. Charo-Karisa H, Gichuri M. Overview of the fish farming enterprise and the aquaculture development strategy 2010-2015. Nairobi: Aquaculture Development Working Group, Ministry of Fisheries Development, 2010.
23. Costa-Pierce BA. Sustainable ecological aquaculture systems: The need for a new social contract for aquaculture development. Marine Technology Society Journal. 2010; 44(3):88-112. Doi: https://www.ingentaconnect.com/content/mts/mtsj/2010/00000044/00000003/art00009
24. De Silva SS, Soto D. Climate change and aquaculture: Potential impacts, adaptation and mitigation. Climate change implications for fisheries and aquaculture: Overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. 2009; 530:151-212.
25. Diana JS, Egna HS, Chopin T, Peterson MS, Cao L, Pomeroy R, *et al*. Responsible aquaculture in 2050: Valuing local conditions and human innovations will be key to success. BioScience. 2013; 63(4):255-262. Doi: https://doi.org/10.1525/bio.2013.63.4.5
26. Dogah W. Studies on aspects of the biology of Clariasgariepinus and Heterobranchuslongifilis from river Offin: Towards their culture development in Ghana (Doctoral dissertation, University of Cape Coast), 2020. http://hdl.handle.net/123456789/4826
27. Edwards P. Aquaculture, poverty impacts and livelihoods. Overseas Development Institute, 2000. http://cdn-odi-production.s3.amazonaws.com/media/documents/2849.pdf
28. E-Jahan KM, Ahmed M, Belton B. The impacts of aquaculture development on food security: Lessons from Bangladesh. Aquaculture Research. 2010; 41(4):481-495. Doi: https://doi.org/10.1111/j.1365-2109.2009.02337.x
29. FAO. Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication. Rome: Food and Agriculture Organization of the United Nations, 2015.
30. FAO. Scoping study on decent work and employment in fisheries and aquaculture: Issues and actions for discussion and programming. Rome: Food and Agriculture Organization of the United Nations, 2021.
31. Food and Agriculture Organization of the United Nations. The State of World Fisheries and Aquaculture 2018: Meeting the Sustainable Development Goals. Rome: FAO, 2018.
32. Froehlich HE, Gentry RR, Halpern BS. Global change in marine aquaculture production potential under climate change. Nature Ecology & Evolution. 2018; 2(11):1745-1750. Doi: https://doi.org/10.1038/s41559-018-0669-1
33. Froehlich HE, Koehn JZ, Holsman KK, Halpern BS. Emerging trends in science and news of climate change threats to aquaculture and the adaptation of aquaculture. Aquaculture. 2022; 549:p737812. Doi: https://doi.org/10.1016/j.aquaculture.2021.737812
34. Gereffi G, Raj-Reichert G. Handbook on global value chains. Edward Elgar Publishing, 2019. Doi: https://doi.org/10.4337/9781788113779
35. Hambrey J. The 2030 agenda and the sustainable development goals: The challenge for aquaculture development and management. FAO Fisheries and Aquaculture Circular (C1141), 2017. https://search.proquest.com/openview/3ac9d20238eabc613e4c90145683fb31
36. Harrison HL, Rybråten S, Aas Ø. Hatching knowledge: A case study on the hybridization of local ecological

knowledge and scientific knowledge in small-scale Atlantic salmon (Salmosalar) cultivation in Norway. Human Ecology. 2018; 46(4):449-459. Doi: https://doi.org/10.1007/s10745-018-0001-3

37. Issa FO, Aderinoye-AbdulWahab S, Kagbu JH. Assessment of aquaculture development programmes in Nigeria. Journal of Agricultural Extension. 2022; 26(1):10-17. Doi: 10.4314/jae.v26i1.2
38. Johannes RE. The renaissance of community-based marine resource management in Oceania. Annual Review of Ecology and Systematics. 2002; 33(1):317-340. Doi: https://doi.org/10.1146/annurev.ecolsys.33.010802.150524
39. Kassam L. Assessing the contribution of aquaculture to poverty reduction in Ghana (Doctoral dissertation, SOAS, University of London), 2013.
40. Kruijssen F, McDougall CL, Van Asseldonk IJ. Gender and aquaculture value chains: A review of key issues and implications for research. Aquaculture. 2018; 493:328-337. Doi: https://doi.org/10.1016/j.aquaculture.2017.12.038
41. Mapfumo B. Regional review on status and trends in aquaculture development in sub-Saharan Africa-2020, 2022.
42. Mbonge J, Musa MS, Orina PS, Kyule DN, Opiyo MA, Charo-Karisa H, *et al*. An Overview of the Current Status of the Kenyan Fish Feed Industry and Feed Management Practices, Challenges, and Opportunities, 2014. https://ir-library.ku.ac.ke/handle/123456789/30324
43. Naylor RL, Hardy RW, Buschmann AH, Bush SR, Cao L, Klinger DH, *et al*. A 20-year retrospective review of global aquaculture. Nature. 2021; 591(7851):551-563. Doi: https://doi.org/10.1038/s41586-021-03308-6
44. Olaoye OJ. Adoption of improved fisheries technologies among fish farmers in Ogun State. FUTA Journal, 2016. https://journals.futa.edu.ng
45. Olaoye OJ, Ashley-Dejo SS, Fakoy, EO, Ikeweinwe NB, Alegbeleye WO, Ashaolu FO, *et al*. Socio-economic determinants of the demand for OSAMCA loan among fish farmers in Remo zone of Ogun State, Nigeria. Journal of Sustainable Development in Africa. 2012; 14(4):197-207.
46. Opiyo MA, Marijani E, Muendo P, Odede R, Leschen W, Charo-Karisa H. A review of aquaculture production and health management practices of farmed fish in Kenya. International Journal of Veterinary Science and Medicine. 2018; 6(2):141-148. Doi: https://doi.org/10.1016/j.ijvsm.2018.07.001
47. Ottinger M, Clauss K, Kuenzer C. Aquaculture: Relevance, distribution, impacts, and spatial assessments-A review. Ocean & Coastal Management. 2016; 119:244-266. Doi: https://doi.org/10.1016/j.ocecoaman.2022.106158
48. Pomeroy R, Dey MM, Plesha N. The social and economic impacts of semi-intensive aquaculture on biodiversity. Aquaculture Economics & Management. 2014; 18(3):303-324. Doi: https://doi.org/10.1080/13657305.2014.926467
49. Primavera JH. Socio-economic impacts of shrimp culture. Aquaculture Research. 1997; 28(10):815-827. Doi: https://doi.org/10.1046/j.1365-2109.1997.00946.x
50. Rector ME, Filgueira R, Bailey M, Walker TR, Grant J. Sustainability outcomes of aquaculture eco-certification: Challenges and opportunities. Reviews in Aquaculture. 2023; 15(2):840-852.
51. Rivera-Ferre MG. Can export-oriented aquaculture in developing countries be sustainable and promote sustainable development? The shrimp case. Journal of Agricultural and Environmental Ethics. 2009; 22(4):301-321. Doi: https://doi.org/10.1007/s10806-009-9148-7
52. Rolls RJ, Heino J, Ryder DS, Chessman BC, Growns IO, Thompson RM, *et al*. Scaling biodiversity responses to hydrological regimes. Biological Reviews. 2018; 93(2):971-995. Doi; https://doi.org/10.1111/brv.12381
53. Saha CK. Emergence and evolution of aquaculture sustainability certification schemes. Marine Policy. 2022; 143:p105196. Doi: https://doi.org/10.1016/j.marpol.2022.105196
54. Samaddar A. Recent trends on Tilapia cultivation and its major socioeconomic impact among some developing nations: A Review. Asian J. Fish. Aquat. Res. 2022; 8:1-10.
55. Tisdell CA. Socioeconomic considerations in the development of aquaculture. In Socio-economics of Aquaculture, Proceedings of International Symposium. 1994; 93:1-13. https://www.researchgate.net/publication/265908073
56. Troell M, Naylor RL, Metian M, Beveridge M, Tyedmers PH, Folke C, *et al*. Does aquaculture add resilience to the global food system? Proceedings of the National Academy of Sciences. 2014; 111(37):13257-13263. Doi: https://doi.org/10.1073/pnas.1404067111
57. Tveterås S, Asche F, Bellemare MF, Smith MD, Guttormsen AG, Lem A, *et al*. Fish is food-the FAO's fish price index. PloS one. 2012; 7(5):p.e36731. Doi: https://doi.org/10.1371/journal.pone.0036731
58. Weeratunge N, Snyder KA, Choo PS. Gleaner, fisher, trader, processor: Understanding gendered employment in fisheries and aquaculture. Fish and Fisheries. 2010; 11(4):405-420. Doi: https://doi.org/10.1111/j.1467-2979.2010.00368.x
59. Williams MJ. Aquaculture and sustainable food security in the developing world. Sustainable aquaculture, 1997, 15-51. https://www.researchgate.net/publication/292159722