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Addressing Catfish (*Clarias* spp.) Supply Gap in Nigeria: A Perspective on Strategies for Sustainable Aquaculture Growth

Kornsorn Srikulnath [1,2,*], Thitipong Panthum [1], Worapong Singchat [1], Aingorn Chaiyes [1], Jiraboon Prasanpan [1,3], Ukam Uno [1,4,5], Uduak Edem [1,4] and Jude Ejikeme Obidiegwu [6,7]

1 Animal Genomics and Bioresource Research Unit (AGB Research Unit), Faculty of Science, Kasetsart University, Bangkok 10900, Thailand; thitipong.pant@ku.ac.th (T.P.); worapong.singc@ku.ac.th (W.S.); aingorn.ch@ku.ac.th (A.C.); jiraboonp@betagro.com (J.P.); ukamuno@yahoo.com (U.U.); edemlinus@unical.edu.ng (U.E.)
2 Biodiversity Center, Kasetsart University (BDCKU), Bangkok 10900, Thailand
3 Kalasin Fish Hatchery Farm (Betagro), Buaban, Yangtalad District, Kalasin 46120, Thailand
4 Department of Genetics and Biotechnology, Faculty of Biological Sciences, University of Calabar, Calabar P.M.B. 1115, Cross River State, Nigeria
5 Department of Biology, University of Education and Entrepreneurship, Akamkpa P.M.B. 1171, Cross River State, Nigeria
6 National Root Crops Research Institute, Umudike P.M.B. 7006, Abia State, Nigeria; ejikeobi@yahoo.com
7 Federal Cooperative College, Oji River P.M.B. 017, Enugu State, Nigeria
* Correspondence: kornsorn.s@ku.ac.th

Abstract

Nigeria's aquaculture sector, which has been dominated by the production of African catfish (*Clarias gariepinus*), has held considerable potential to improve national food security, support livelihoods, and contribute to economic growth. Although Nigeria has been ranked among the world's leading producers of farmed catfish, a persistent fish supply deficit that exceeds 2.5 million metric tons annually has been reported. This gap has been sustained by factors such as low productivity, genetic decline, inadequate hatchery systems, and limited export competitiveness. A comprehensive perspective is presented in this review, in which findings from recent researches, field surveys, and stakeholder consultations have been synthesized. The dominance of hybrid species such as *Heteroclarias*, which has been driven by consumer demand due to fast growth and large body size, is highlighted. Additionally, ecological and genetic concerns resulting from unregulated breeding are emphasized. Major systemic constraints, which include poor broodstock management, weak hatchery infrastructure, low technical capacity, and poor supply chain governance, have also been identified. A strategic approach involves modernizing fish breeding programs by developing a robust and active Fish Breeding Community of Practice (FCoP), enhancing physical infrastructure, improving data collection and management, standardizing germplasm exchange procedures, and increasing the number and capacity of fish breeders and technicians in breeding programs. Identifying traits preferred by farmers and end-users ensures that fish breeding is demand-driven and inclusive. Building capacity in genomic resources to implement an accurate predictive platform for performance assessment will significantly shorten the breeding cycle and increase the rate of genetic progress. This will be complemented by the adoption of modern aquaculture technologies, such as recirculating aquaculture systems, and the development of institutional frameworks for production, certification, and traceability schemes. Capacity development, which should be promoted through collaboration among academic institutions, industry actors, and government agencies, has been recommended. The alignment of aquaculture expansion with environmental sustainability, improved biosecurity, and habitat protection has been considered critical. By outlining strategies for innovation, investment, and policy

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Received: 16 September 2025
Revised: 22 October 2025
Accepted: 24 October 2025
Published: 30 October 2025

Citation: Srikulnath, K.; Panthum, T.; Singchat, W.; Chaiyes, A.; Prasanpan, J.; Uno, U.; Edem, U.; Obidiegwu, J.E. Addressing Catfish (*Clarias* spp.) Supply Gap in Nigeria: A Perspective on Strategies for Sustainable Aquaculture Growth. *Sustainability* **2025**, *17*, 9645. https://doi.org/10.3390/su17219645

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reform, this review provides a roadmap through which Nigeria's catfish industry can be transformed into a globally competitive and sustainable sector.

Keywords: catfish aquaculture; *Clarias gariepinus*; *Heteroclarias*; sustainable aquaculture; fish supply gap; genetic improvement; Nigeria fisheries sector

1. Introduction

Aquaculture is the fastest-growing animal food production sector globally, accounting for over 50% of the fish consumed worldwide [1–3]. It plays a crucial role in ensuring food and nutritional security, particularly in developing countries [4,5]. Aquaculture production in Nigeria reached an estimated 260,000 t in 2023 and is projected to decline to ~240,000 t by 2028 [6]. This trend corresponds to a compound annual decline rate (CAGR) of 1.3%. Among the farmed fish species, catfish and tilapia have been reported to account for approximately 80% of total production. However, the total annual fish demand in Nigeria has been estimated to exceed 3.6 million metric tons, which results in a persistent supply deficit of approximately 2.5 million metric tons per year [7]. To address this shortfall, between 700,000 and 900,000 metric tons of fish have been imported annually, which accounts for nearly 40% of the country's domestic fish supply, while the remaining is sourced from local farmers and fishermen [8].

Nigeria has been regarded as the leading producer of farmed catfish in Sub-Saharan Africa (SSA). Although it supplies fish to both domestic and regional markets, its contribution to international exports remains very limited [9–11]. The share of aquaculture in total catfish production, which includes both aquaculture and capture fisheries, has increased from 5.1% in 2001 to 30.8% in 2015 [12,13]. Over the past decade, the expansion of catfish farming has been recognized as a major driver of aquaculture development in Nigeria, which has contributed over 60–70% of the country's total aquaculture output [11]. The African catfish (*Clarias gariepinus*) and its heteroclarias hybrids have been identified as the dominant cultured species, and contribute approximately 50–55% of the national aquaculture production by volume [9,14]. The *Clarias* catfish industry has been described as a cornerstone of the Nigerian aquaculture sector. It has been estimated that this industry supports 1–3 million livelihoods, which include farmers, fishers, and market operators [7,15]. Furthermore, the industry contributes significantly to national income and foreign exchange earnings [16]. Approximately 150,000 catfish farms and hatcheries of different scales, which range from backyard earthen ponds to commercial recirculating aquaculture systems (RASs), have been registered nationwide [17,18]. The development of aquaculture in Nigeria has been traced to initiatives that were introduced in the 1960s, which progressed slowly until a rapid expansion was observed after the year 2000 [19].

This rapid growth has been linked to various government programs that were designed to increase domestic fish production, reduce dependence on imports, and support the growth of export markets [20,21]. As a result, total aquaculture production has increased from less than 441,377 metric tons in 2000 to over 805,210 metric tons in 2021, and this reflects an average annual growth rate of approximately 2.90% over the past two decades [22]. Despite these improvements, it has been observed that productivity within Nigeria's African catfish industry is still constrained by underdeveloped breeding infrastructure. A large proportion of small- and medium-scale hatcheries have continued to rely on wild-captured or recycled broodstock, as documented in Food and Agriculture Organization (FAO) reports on regional broodstock dependence [23]. This practice has contributed to widespread inbreeding, a reduction in broodstock vigor, and an increase in

disease susceptibility [24]. Poor-quality or recycled broodstock can reduce fingerling survival by 25–35% and growth by 15–25% compared with improved strains [15,25]. It has also been reported that only a small number of hatcheries in Nigeria use standardized breeding protocols or keep proper records of broodstock pedigree and genetic traits [26,27]. These challenges are further compounded by limited access to improved genetic material, weak biosecurity in hatcheries, and inadequate extension services [28]. In addition to technical constraints, broader issues such as unsustainable farming practices, the environmental impact of wild broodstock harvesting, and price fluctuations in fish markets have also been identified [29]. The lack of comprehensive documentation that captures real-time challenges faced by producers and traders at the grassroots level has been considered a key limitation for policy formulation and sectoral planning [30,31]. Nevertheless, aquaculture remains an essential livelihood source for more than 10 million Nigerians who are engaged in both primary and secondary fish production activities [3,11]. Although Nigeria's fishery sector has been recognized to have strong potential, sustained growth and national self-sufficiency will require coordinated efforts to address existing technical, economic, and environmental constraints [2,11,32].

This review is aimed at integrating perspectives from stakeholders and findings from existing studies, surveys, and expert interviews that have involved wild fish harvesters, catfish farmers, hatchery operators, industry representatives, and market traders. The objective is to assess the current state of catfish aquaculture in Nigeria, identify key challenges and opportunities, and explore potential strategies for sustainable development. It is expected that a better understanding of market dynamics, ecological impacts, and policy gaps will provide a foundation for effective decision-making, long-term industry resilience, and global competitiveness in the Nigerian fish trade.

2. Industry Overview

Insights into the feasibility and trends of catfish aquaculture in Nigeria have been gathered from stakeholders representing various points along the value chain. These stakeholders include small- and medium-scale fish farmers, wild broodstock harvesters, hatchery operators, processors, exporters, and fish traders who operate in key production and marketing regions. Data were collected from Lagos, which serves as Nigeria's primary commercial hub; Kano, which has been identified as an inland aquaculture center; and the Niger Delta region, which is known for its abundance of wild fish resources and strong tradition for wild fish harvesting (Figure 1). This cross-regional approach was adopted to reflect the diversity of production systems, ecological contexts, and market dynamics that exist across Nigeria. Nigeria has been widely recognized as the largest producer of farmed African catfish (*C. gariepinus*) in SSA. The country has been estimated to produce between 250,000 and 300,000 metric tons annually, with a market value of over USD 350 million [33]. However, most of this production has been consumed domestically or traded regionally within West Africa. Only a small portion has been exported to niche markets in Europe and the Middle East, primarily to meet the demand of African diaspora communities [32,34]. In contrast, countries such as Uganda and Kenya have exported modest volumes of fingerlings and processed catfish products to other African nations, and this highlights Nigeria's relatively small presence in global catfish trade [35]. Moreover, comparative evidence from Egypt, Ghana, and South Africa provides useful context for benchmarking Nigeria's aquaculture development. Egypt remains Africa's leading aquaculture producer, contributing over 70% of continental output through highly organized tilapia and catfish farming systems supported by national broodstock centers and strong policy frameworks [17]. Ghana has achieved significant progress in catfish seed quality and farm certification through the Fisheries Commission's Aquaculture Directorate,

resulting in improved hatchery performance and feed efficiency [22]. South Africa, though producing smaller volumes, emphasizes quality control, export-oriented processing, and environmental compliance, providing a model for integrating sustainability with market competitiveness [10].

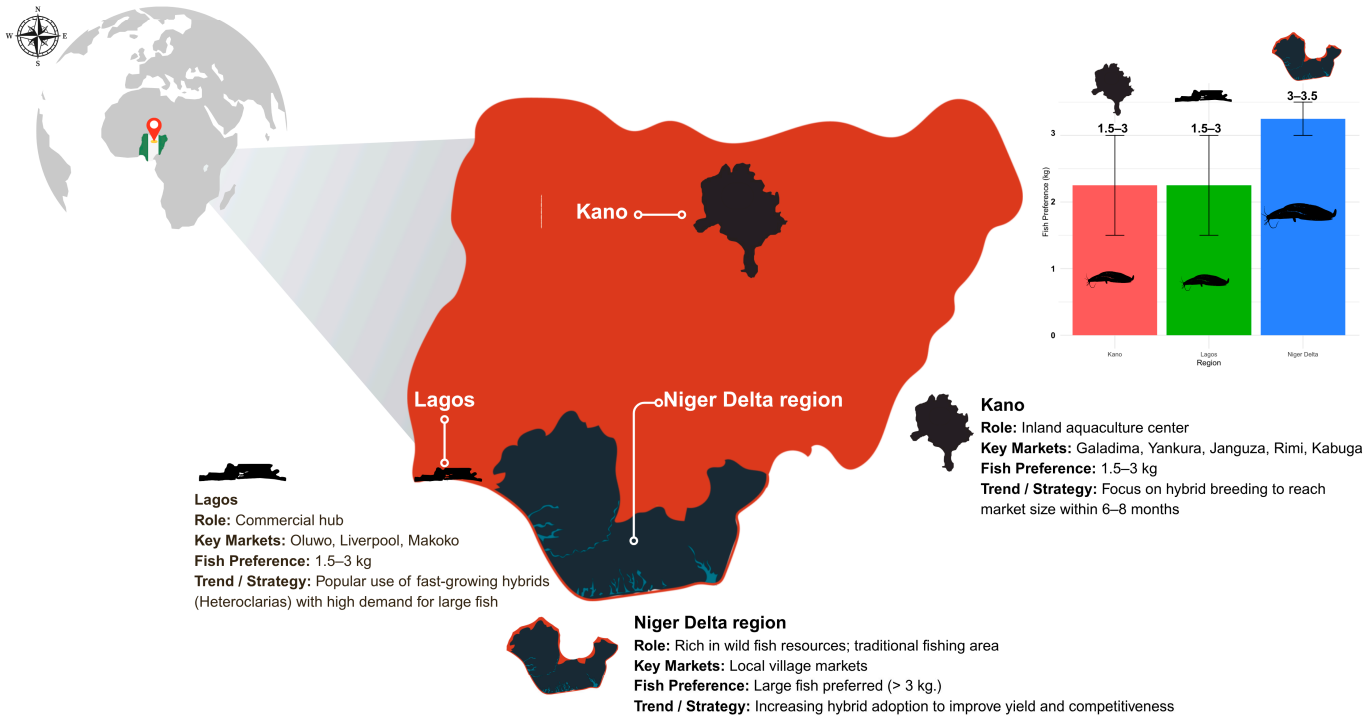


Figure 1. Catfish aquaculture trends in Nigeria from key stakeholders across the value chain in Lagos, Kano, and the Niger Delta (The red color represents Nigeria, the dark blue color indicates the regions and stages within Nigeria).

The demand for Nigerian catfish in international markets has been influenced by competitive pricing and growing awareness of fish as a nutritious, protein-rich, and sustainable food source [3,12]. To strengthen Nigeria's position in high-value export markets, improvements are required in product quality, safety standards, and supply chain traceability. These improvements must be supported by investment in certification schemes such as Global Good Agricultural Practice (GLOBALG.A.P.), cold chain infrastructure, and transparent supply chain management, which are crucial for accessing high-value markets in the EU and Asia [22,36]. However, it has been reported that Nigerian exporters face several operational challenges. Delays, limited cold storage, and variable product quality increase post-harvest losses and reduce profitability [37].

It has been suggested that the use of genetically improved hybrid strains, such as *Heteroclarias*, which are produced by crossing Vundu or Sharptooth catfish (*Heterobranchus longifilis*) with African catfish (*Clarias gariepinus*), could help improve yield and competitiveness [15]. These hybrids have been reported to reach lengths of up to 1.5 m and weights between 30 and 60 kg [38]. Such traits are desirable in both domestic and export markets. Across major urban fish markets in Nigeria, such as Oluwo (Epe), Liverpool, and Makoko Markets in Lagos [39,40]; Galadima, Yankura, Janguza, Rimi, and Kabuga Markets in Kano [41]; and the Eriwe Fish Farm Village Market in Oyo State [42], a strong preference for large fish has been consistently observed. Fish that weigh between 1.5 and 3 kg are preferred because they are perceived to offer better meat yield, greater value for money, and higher profitability for traders and farmers [32,37,43]. To meet this demand, many farmers have chosen to breed fast-growing hybrids that can reach market size within 6 to

8 months to maximize profits. This demand has fostered the proliferation of hybrid breeds, particularly hybrid catfish (*Heteroclarias*) [11,21,44]. *Heteroclarias* hybrids have become widely adopted due to their ability to combine the rapid growth and disease tolerance of *Clarias* with the large body size and hardiness of *Heterobranchus* (Figure 2) [15,45,46]. Stakeholders have reported that *Heteroclarias* can exhibit superior growth rates and survival compared with pure *Clarias* strains [11,47] to reach a market weight of 1.5 to 2 kg in less than 8 months under optimal feeding and management conditions [23,25,38]. This allows farmers to achieve faster turnover and higher income.

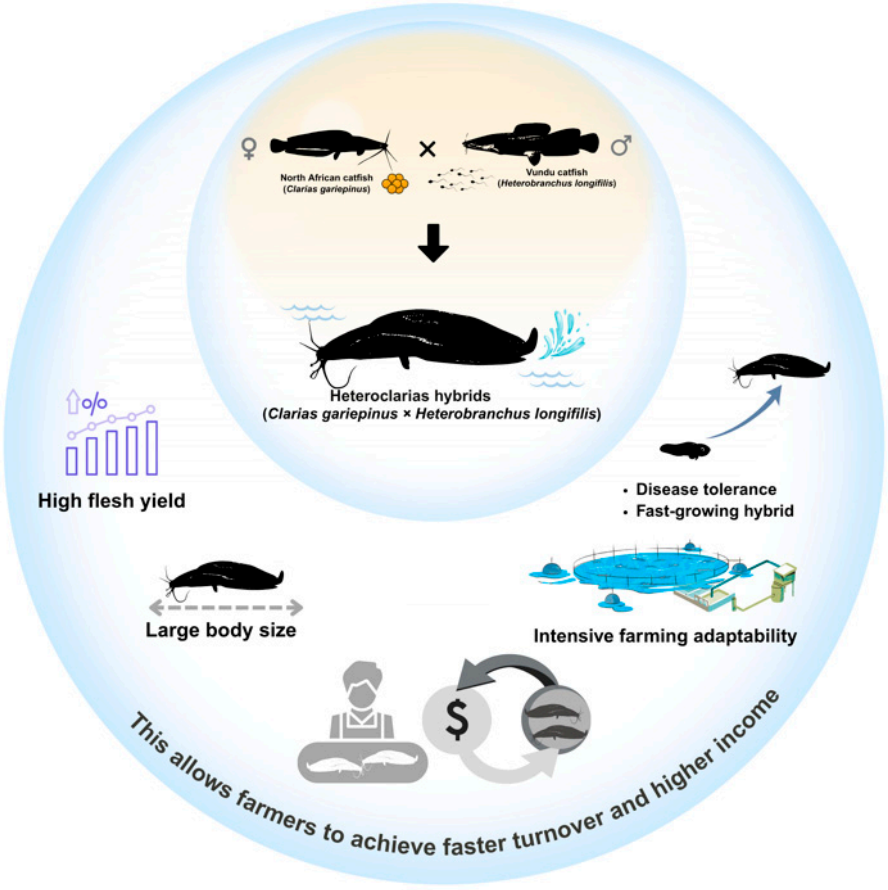


Figure 2. Growth advantages and production performance of *Heteroclarias* hybrids in aquaculture. (The arrow indicating high flesh yield represents higher production, while the arrow for large body size shows that the hybrid exhibits both larger body size and faster growth).

Although *Clarias gariepinus* has continued to be valued for its taste and adaptability, the commercial production of hybrids such as *Heteroclarias* has become more dominant. This shift has occurred due to economic incentives and market-driven pressures [15,44,48,49]. Privately operated breeding initiatives have emerged in response, but they are often implemented without formal genetic management or certification schemes. Nigeria's breeding systems have remained largely informal and fragmented, and no comprehensive national program has been implemented to ensure consistent genetic improvement or quality control [2,11]. Hence, many farmers use uncertified hybrid fingerlings of uncertain genetic origin and variable quality, which may result in inconsistent production outcomes and reduced industry reliability [11]. The current production model has been designed to prioritize high-yield, short-cycle farming practices that focus on market demands for size and volume [43,50]. Although this model has enabled farmers to achieve quicker returns, it has also led to reduced attention to ecological sustainability and genetic diversity [24,27]. This approach results in quality inconsistencies, limited traceability, and challenges related

to certification that impede access to high-value foreign markets [24,27]. Port delays and weak cold chains complicate exports, causing spoilage and lower profits [12,51]. To address these issues, stakeholders have emphasized the importance of scaling breeding programs to improve quality assurance, implement traceability systems, and upgrade logistical infrastructure [21]. Many farmers have also operated with minimal awareness of genetic protocols, disease control strategies, or record-keeping systems for broodstock selection [28]. This has contributed to the erosion of genetic diversity in native *Clarias* populations, which increases vulnerability to diseases and reduces resilience under changing environmental conditions [15,52]. Consumer preferences, especially among urban, middle-, and upper-income groups, have gradually shifted toward fish that are considered to be fresher, safer, and more sustainably farmed. However, the majority of consumers in local markets still base their purchasing decisions primarily on affordability and size [12].

This situation has encouraged the continued production of fast-growing hybrids, despite concerns about long-term sustainability. The strong market orientation toward rapid growth and large size has influenced breeding priorities, often at the expense of environmental sustainability and genetic conservation [27,53]. Moving forward, there is a need to integrate consumer-driven traits with sustainable breeding practices to maintain productivity and reduce ecological risks. This will require coordinated investment in genetic resource management, certification systems, infrastructure development, and stakeholder training to ensure that Nigeria's catfish aquaculture sector can achieve long-term growth and international competitiveness.

Nigeria's aquaculture sector has been dominated by the cultivation of *Clarias gariepinus* and *Heterobranchus longifilis*, which together account for over 80% of the farmed catfish produced in the country [15]. These species have been selected because they are highly adaptable to Nigeria's diverse environmental conditions and resilient to many of the common diseases that affect aquaculture. In Nigeria, optimal environmental conditions for catfish breeding typically include a water temperature range of 26–30 °C, dissolved oxygen above 5 mg/L, pH between 6.5 and 8.0, and moderate water hardness (40–120 ppm). These conditions are most suitable for induced spawning, egg fertilization, and fry development in both earthen ponds and hatchery systems. In addition, they have been shown to perform reliably in a range of production systems that include both earthen ponds and cage culture [7,54]. In recent years, hybrid catfish, particularly *Heteroclarias*, have been adopted more frequently by fish farmers. These hybrids have been favored due to their rapid growth rates, larger adult size, and improved disease resistance compared with the parent species [30,50]. It has been estimated that these hybrids generally achieve better feed conversion ratios (FCRs), which are approximately 1.5:1 to 2.0:1 compared with 2.0:1 to 2.5:1 for traditional *Clarias* under similar farm conditions [47,55]. This implies that only 1.5 to 2 kg of feed are needed to produce one kilogram of fish, and this indicates a significant reduction in feed costs. As feed has been reported to account for 60–70% of total production expenses in commercial operations, this improved efficiency has been critical to farm profitability [56,57].

The rapid growth rates and favorable FCRs of *Heteroclarias* hybrids have been considered attractive for production systems that aim to complete multiple production cycles per year. Under optimal conditions [15,21], marketable weights ranging from 1.2 to 1.5 kg can be reached within 6 to 8 months [47,55]. These fish are typically raised in controlled systems such as concrete tanks, where their growth performance and health can be more easily managed [58–60]. In terms of market consumption, the domestic Nigerian market has been characterized by a division in consumer preferences. Approximately 64% of consumed catfish has been identified as *Clarias gariepinus*, which is preferred for its traditional taste, affordability, and familiar growth patterns [22,61]. The remaining 40% is composed of

hybrid *Heteroclarias*, which have gained popularity due to their rapid growth, larger size, and compatibility with intensive farming systems [62]. However, these proportions vary by region. In urban centers such as Lagos, Abuja, and Port Harcourt, or agriculturally advanced states like Oyo and Ogun, where farmers have better access to high-quality feed, breeding stock, and inputs, *Heteroclarias* have been reported to comprise over 54% of the market share. In contrast, rural areas such as parts of Benue, Taraba, and Kebbi States have remained more dependent on native breeds and wild-caught fish [2]. Nationally, more than 80 percent of Nigeria's total domestic fish supply originates from artisanal small-scale fishers in coastal, inshore, creek areas of the Niger Delta, lagoons, inland rivers, and lakes [63]. The preference for hybrid catfish, particularly *Heteroclarias*, has been driven by a production model that emphasizes rapid turnover and high yields, raising concerns about ecosystem impacts and the potential for gene flow between wild and farmed populations [15,63–68].

The industry's reliance on hybrids, which has been motivated by the drive for quick profit and high production output, has emphasized the need for structured breeding programs, genetic certification mechanisms, and improved sustainability practices. The structure of Nigeria's aquaculture market, where large, fast-growing hybrids with favorable FCRs are strongly preferred, has presented both an economic opportunity and a critical challenge. On the one hand, there is the potential for continued expansion based on profitability. On the other hand, long-term growth will depend on the development of breeding strategies that are scientifically managed and ensure genetic stability and resilience across production systems [11].

3. Developing a Complete Breeding Program in Nigeria

An effective and sustainable catfish breeding program in Nigeria must be established through a strategic focus that includes germplasm conservation, systematic genetic evaluation, and post-breeding broodstock management. Given Nigeria's climate is heterogeneous and becoming more variable, breeding must explicitly preserve adaptive variation. Practically, programs should maintain sufficiently large effective population sizes, conduct multi-environment trials (METs) across representative agro-ecological zones, quantify genetic and environmental (G × E) variance and reaction norms for candidate lines, implement genomic monitoring to track allele frequency changes at candidate adaptive loci, include adaptability measures in selection indices, use forward simulation modeling to compare breeding strategies, and set acceptable trade-offs between short-term gain and long-term adaptive potential. These measures allow for the empirical quantification of adaptive risk and provide operational thresholds for program governance [69,70]. The collection and preservation of diverse germplasm, which should be sourced from multiple original locations across Nigeria and selected according to biological zones, must serve as the foundation of this approach [12,70]. A broad genetic base that consists of diverse germplasm is essential for maintaining a founder stock with high genetic variability, which is regarded as necessary for long-term genetic improvement and environmental adaptability [71,72]. The preservation of such diversity is required to prevent inbreeding depression and retain a wide spectrum of genetic traits that are crucial for the success of future selective breeding programs [71,73]. A baseline population, which must be derived through random mating among individuals that originate from different locations, should be created from this germplasm. According to the principles of population genetics, six generations of random mating are required before a genetically stable baseline population with balanced heterozygosity and a well-defined genetic structure can be achieved [74]. This baseline serves as the foundation for systematic genetic improvement (Figure 3). This population should serve as the platform from which systematic genetic improvement is conducted.

Once this baseline has been established, performance data and molecular markers should be used to guide directional selection [75].

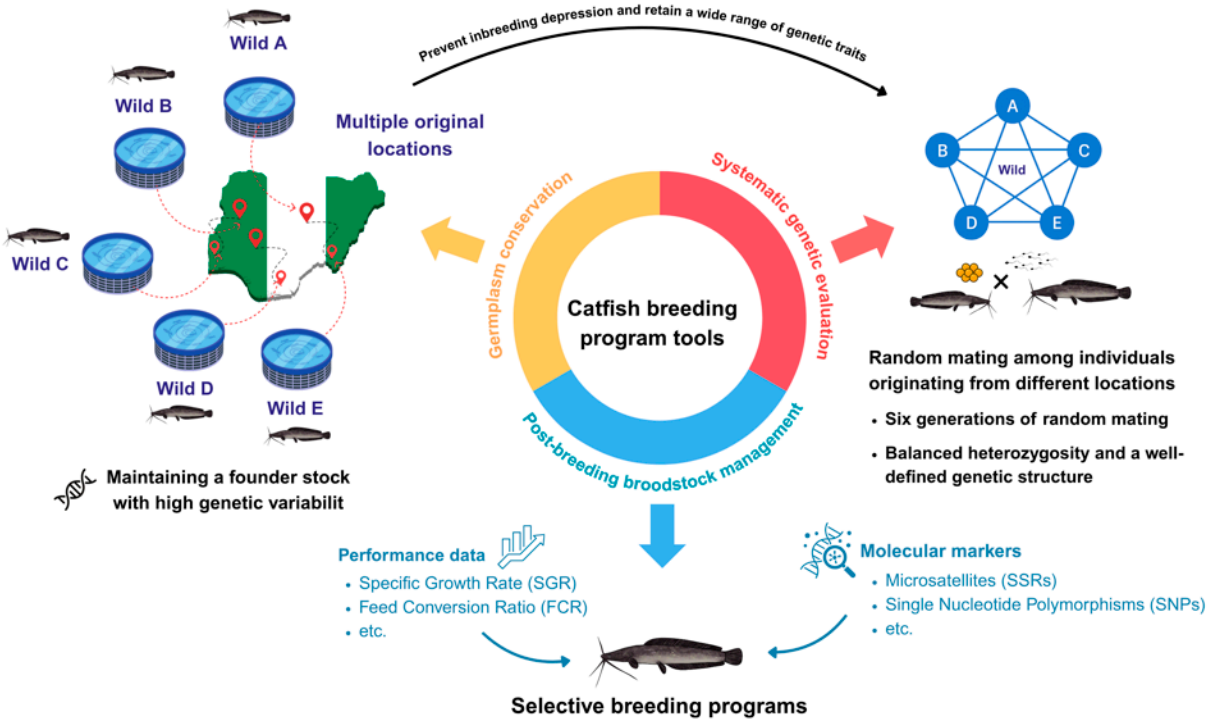


Figure 3. Catfish program breeding tools supporting systematic genetic improvement for catfish breeding programs. (The arrows surrounding the circles illustrate the separation of each section (yellow, pink, and blue). Arrows originating from multiple sources indicate the process of systematic genetic evaluation aimed at preventing inbreeding depression. The arrow from the post-breeding broomstick represents the integration of performance data and molecular markers for use in selective breeding programs of catfish).

When marker-assisted selection (MAS) is applied, desirable alleles that are associated with traits such as faster growth, high FCR, and disease resistance can be identified and propagated more rapidly, although environmental and management conditions such as temperature, dissolved oxygen, feed quality, stocking density, water chemistry, and husbandry can markedly change both the phenotypic means and heritability estimates and create important G × E interactions [76,77]. However, a staged uptake of molecular tools is necessary, which entails improving record-keeping and reconstructing pedigrees with parentage single nucleotide polymorphism (SNP) panels, running nucleus breeding hubs to concentrate genotyping and phenotyping investments, and applying MAS/genomic selection selectively once reference populations reach an adequate size. This pragmatic pathway reduces the upfront costs and increases the return on investment in molecular tools [77]. Decisions made during breeding should be supported by trend analyses of genetic markers, which will allow for the development of breeding lines that are tailored for specific traits such as accelerated growth, improved feed efficiency, or enhanced environmental resilience [15,78].

For practical breeding planning, it is useful to place numerical expectations on key parameters. Published work in *Clarias* and closely related catfish indicates moderate heritability (h^2) for growth (body weight/length) typically in the range ~0.20–0.40, whereas FCR tends to show lower to moderate heritability (~0.10–0.30), and disease-resistance traits are more variable. To limit inbreeding while sustaining selection response, breed-

ing programs should set an effective population size (N_e) target. A pragmatic target is $N_e \geq 50$ for short-term sustainability, with a longer-term objective of $N_e \geq 500$ to retain adaptive potential [76,78]. Breeding programs should also increase breeder numbers or adopt rotational mating/factorial designs and nucleus-hub schemes to raise the N_e and manage the rate of inbreeding. Routine monitoring of pedigree or SNP-based inbreeding estimates is recommended to keep the realized inbreeding rate (ΔF) below ~1% per generation [70,71,76,78].

Reproductive technologies that include hormone-induced spawning, artificial fertilization, and controlled incubation must be implemented within modern hatchery systems [79,80]. These technologies enable a high degree of control over reproductive events, which ensures predictable outcomes and high-quality offspring. Post-breeding broodstock management, which is equally important, must be guided by protocols that ensure optimal broodstock health, maintain strict genetic oversight, and retain detailed pedigree and trait performance records [65,81]. New elite individuals, which must periodically be introduced from the founder populations, are required to maintain high genetic quality and prevent inbreeding depression [82–84]. A breeding infrastructure that can support these efforts must be constructed through the integration of three core elements: the collection of diverse genetic resources; development of a robust baseline population through multiple generations of random mating; and use of advanced selection methods that include both phenotype-based and molecular marker-guided approaches [70,85]. When these are combined with rigorous broodstock management practices, genetically improved fingerlings of high quality can be produced. These improvements are expected to enhance overall productivity, support long-term sustainability, and strengthen Nigeria's position in the global aquaculture industry. At present, Nigeria's aquaculture industry operates without the establishment of a formal, scientifically organized breeding program [26,32]. Broodstock that has been used across the sector has mostly been sourced from uncontrolled origins, which include wild populations and local stocks for which no documented lineage has been maintained, and results in a genetically unstructured and highly variable broodfish pool [26,57]. This uncoordinated approach has caused the occurrence of inconsistent performance, low production efficiency, and limited opportunities for genetic improvement [86,87]. In actual practice, uncertified broodfish that have often been collected randomly from wild stocks or local farms without any pedigree records or genetic evaluation have been routinely used by hatcheries and farmers [88,89].

This unmanaged system has undermined the prospects for targeted genetic improvement, allowed the accumulation of inbreeding and genetic drift, and obstructed the deliberate enhancement of performance traits such as growth rate, FCR, disease resistance, and marketable harvest size [26]. Consequently, stagnation in industry-wide productivity has been observed, and the advantages that are usually associated with structured breeding programs have not been realized [2,90]. These circumstances highlight an urgent need for a structured, science-based breeding framework to be developed and implemented in Nigeria. Aquaculture contributes 2.4–3.0% of Nigeria's agricultural GDP and supports about 250,000 direct and over 1 million indirect livelihoods [13,22]. In major producing states such as Oyo, Ogun, and Delta, women account for 32–38% of hatchery and processing roles, while youth (18–35 years) represent 45–50% of grow-out operations [2,20]). Average household income from catfish farming ranges between ₦ 1.2–1.8 million, varying with feed cost, credit access, and market proximity [13,21]. Socio-cultural and environmental evaluations combine household surveys, key-informant interviews, and farm-level life cycle or rapid environmental assessments focusing on energy use, effluent load, and water exchange. These metrics provide baselines for designing inclusive and sustainable breeding programs [91,92].

A breeding system that would follow the principles of germplasm conservation, phased development of founder stocks, and construction of a genetically balanced baseline population, previously outlined, must be established. The successful development and implementation of such a comprehensive breeding system is required to ensure genetic stability, enhance the quality of cultured stocks, and fully exploit Nigeria's aquaculture potential [11,32]. A 3–4% genetic gain per generation in growth rate can reduce the feed cost per kg by 5–7% and shorten grow-out time from approximately 180 to 150 days [15]. If adopted by 60% of farms, such an improvement could raise the national catfish market value by an estimated ₦ 60–₦ 80 billion annually, boost domestic supply by approximately 25%, and lower frozen-fish imports by 10–12% within five years [13,15,22].

Achieving this objective will depend on coordinated efforts that must involve government agencies, research institutions, industry stakeholders, and private investors. Substantial investments must be committed toward the creation of a breeding center, capacity-building of technical personnel, and deployment of appropriate genetic and reproductive technologies [11,49]. Despite the considerable start-up costs, the long-term benefits, which include measurable gains in productivity, improved disease resistance, efficient resource utilization, and enhanced competitiveness in export markets, are expected to outweigh the initial expenditure. A reliance on fragmented and genetically unmanaged broodstock systems can no longer be sustained. It is imperative that Nigeria prioritize the development of a coordinated, multi-generational breeding program that adheres to modern genetic principles, utilizes advanced biotechnology, and complies with international best practices. This shift must be treated as a national priority to enable the transition from unsystematic production methods to a sustainable and commercially robust aquaculture industry that can reliably meet future domestic and international demand.

4. Hatchery and Farming Systems: Current Status, Challenges, and Opportunities

Nigeria's hatchery sector has remained critically underdeveloped, with fewer than six corporate hatcheries, mostly around Lagos, Port Harcourt, and several other urban centers [2,93]. These hatcheries produce fewer than 500,000 fingerlings annually, which has been vastly insufficient to meet the demands of the sector. Estimates have shown that approximately 10 to 15 million fingerlings per year would be required to sustain current and expanding aquaculture operations, which has reflected a supply shortfall of over 90% [2,31,93]. As a result, most fish farmers depend on wild-caught fingerlings or imported stocks, which lack genetic control, biosecurity, and consistency [17,94]. These practices have led to survival rates that rarely exceeded 30%, and in suboptimal conditions, they have fallen even lower and consequently limited productivity and growth potential [17]. Farmers have mainly operated in traditional pond systems, and it has been estimated that 90% of farmed fish have been produced in small, low-input earthen ponds that typically stock fewer than 10,000 fish per hectare [21,95,96]. These farms often lack proper water management, disease control, or biosecurity protocols, which makes them highly susceptible to outbreaks of bacterial diseases such as motile *Aeromonas septicemia* (MAS) and protozoan infections such as hexamitiasis [97,98]. Each year, approximately 30% of farms experience significant disease outbreaks, which have caused high mortality and economic losses estimated at several billion of Naira across the sector [99]. These smallholder farms have produced modest yields, often below 1 ton per hectare per year, and have operated with high input costs, especially due to low feed efficiency [100,101] (Figure 4). Feed quality has remained a major constraint, as over 80% of farmers depend on homemade or low-cost feeds that lack essential nutrients, and led to poor growth and FCRs of approximately 3:1. This ratio means that nearly twice as much feed is required to produce each kilogram of fish [102,103].

In contrast, well-managed commercial farms that used formulated feeds have reported FCRs of approximately 1.5:1, a benchmark for profitability [56]. This elevated FCR has increased operational costs by up to 100%, which has severely limited profit margins and discouraged scaling.

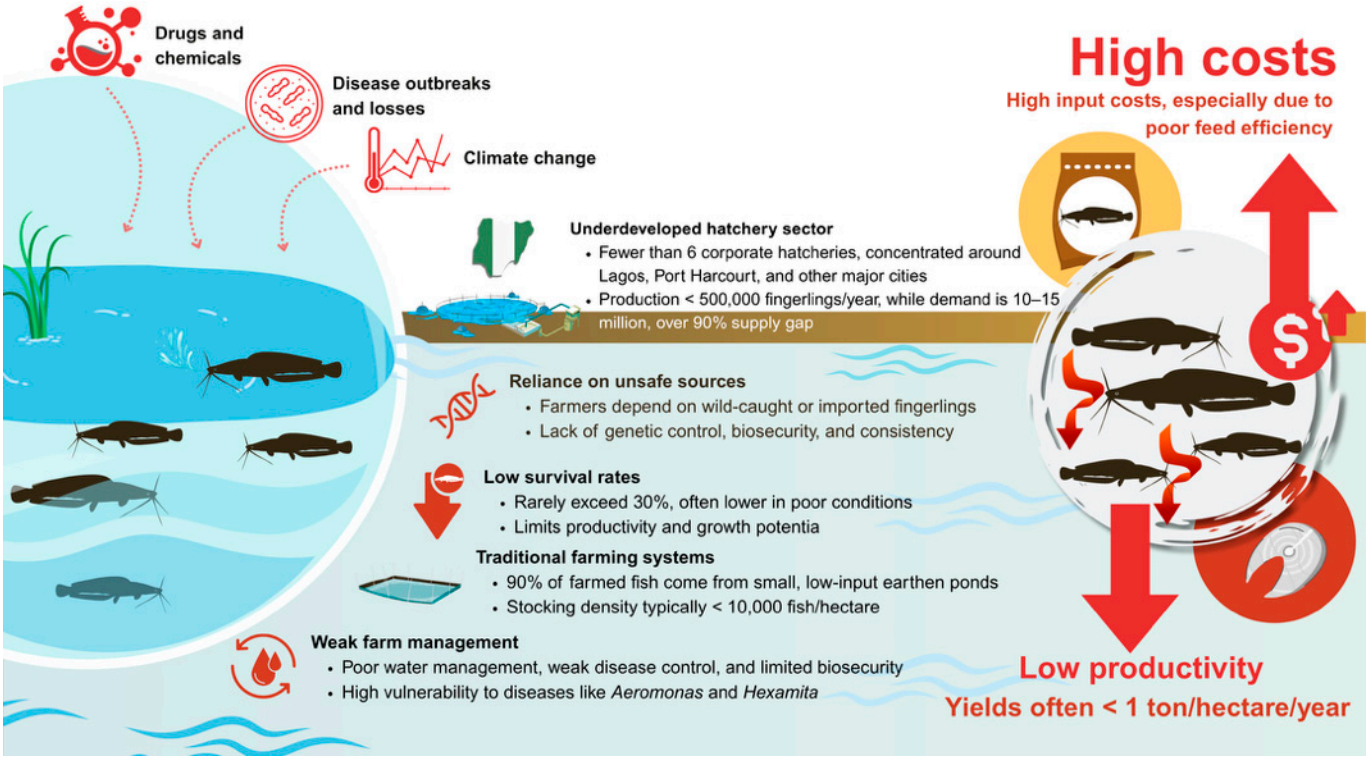


Figure 4. Factors affecting the production performance of smallholder catfish farms.

Access to modern technologies such as automated feeders, water quality sensors, and disease diagnostics has remained very limited, especially for small-scale farmers [104]. Most farmers lack technical expertise, which has caused suboptimal water management, poor disease prevention, and low survival rates [32]. The shortage of skilled personnel has been shown by the fact that only approximately 10–15% of farms employ trained technicians or applied best practices in hatchery and farm management [105]. Nigeria's hatchery infrastructure has been insufficient not only in quantity, but also in operational quality [106]. Existing hatcheries have generally functioned with rudimentary equipment and limited disease control, without the use of advanced genetic or reproductive technologies [30,107]. This situation has led to a stagnant fingerling supply chain, which has hampered genetic improvement efforts and caused inconsistent stock performance across farms [2].

Resolving these systemic problems will require urgent actions, such as the expansion of hatchery infrastructure, improvement of breeder and seed quality, provision of specialized technical training, and promotion of high-quality feed and disease management strategies. With such a foundation, Nigeria's aquaculture sector will be able to improve survival rates, optimize FCR, and grow sustainably. This will enable the sector to move from fragmented, low-yield operations to a cohesive, high-performing value chain that will meet increasing domestic demand and improve export competitiveness.

5. Capacity Building and Knowledge Transfer in Nigeria's Aquaculture Sector

A major constraint that has been observed in Nigeria's aquaculture industry is the limited technical capacity that exists among farmers and hatchery operators [11,108]. For-

mal, structured training in areas such as hatchery management, pond management, disease control, water quality, and sustainable aquaculture has not been accessed by more than 70% of farmers [21,109]. As a result of this skills gap, survival rates have remained low, between 20–30%, and growth rates have remained slow, and these have led to prolonged production cycles, reduced profitability, and limited scaling of the industry [97,98]. These challenges must be addressed through systematic, nationwide capacity-building programs that are tailored to the needs of the local aquaculture industry [13,15]. The programs that should be implemented must contain training in modern hatchery techniques, selective breeding, disease diagnostics, biosecurity, optimized feed formulation, and water quality management, all of which are necessary for improving productivity, fish health, and environmental sustainability [110].

At present, programs that have been implemented by development agencies and government institutions have remained limited in their coverage and impact [111]. A nationwide scale-up of these efforts could raise fingerling production by 200–300%, improve yields, and allow Nigeria to achieve greater self-sufficiency while improving export competitiveness [11]. In addition to technical knowledge, entrepreneurship that supports aquaculture along its value chain should also be encouraged if an inclusive and resilient sector is to be developed [112]. Models that have been designed to integrate aquaculture with feed manufacture, hatchery services, processing, and marketing could generate employment, improve rural livelihoods, and create more robust supply chains [113].

Social enterprises and entrepreneurs who are active in aquaculture could introduce low-cost hatchery technologies, regional breeding hubs, and farmer-centered management schemes, all of which would improve access to quality inputs and services for women, youth, and smallholders. These groups can be engaged through targeted training programs, microcredit schemes, and inclusive cooperatives that enhance their participation in hatchery operations, feed production, and fish processing enterprises [114,115]. Sustainable practices that relate to environmental monitoring, heavy metal testing, eco-friendly pond systems, and resilience to climate change are also being promoted through such initiatives [116]. By connecting skills development with inclusive innovation, a more resilient aquaculture sector could be established in Nigeria, and this would improve production and promote social equity, environmental care, and economic diversification.

Universities and agricultural colleges in Nigeria, which possess aquaculture infrastructures that are relatively underused, should be developed into centers for training, innovation, and knowledge dissemination. These academic institutions contain aquaculture facilities that have the potential to serve as hubs where research, innovation, and skills development can be carried out. If dedicated aquaculture farms are developed on university campuses, practical learning would be enabled for students, producers, and new entrepreneurs, and research could be performed on breeding, nutrition, health, and sustainability. These farms, which are located at academic institutions, could also serve as pilot sites where best practices are demonstrated, technologies are introduced, and replication across other regions is supported. This approach has already been applied successfully in countries such as Thailand, Vietnam, and Namibia [117,118].

A triple helix model, which is a framework that connects academia, industry, and government, should also be used to support coordinated growth. In this model, universities and research centers are responsible for scientific development and training; government agencies are responsible for regulation, infrastructure, and policy; and private companies are responsible for commercialization and employment creation. These three sectors, which are linked through institutional arrangements, create a feedback system that is based on knowledge sharing, policy alignment, and market responsiveness [119,120]. Through this collaboration, genetic improvement programs, biosecurity frameworks, ecological monitor-

ing, and processing technologies can be advanced. At the same time, policies that are better suited to the needs of the industry can be designed with input from multiple stakeholders.

Universities, which can also support business incubation and entrepreneurship, have a key role in promoting inclusive growth by providing opportunities that allow youth and women to participate fully in the aquaculture industry. The formation of strong partnerships between government, academia, and industry, which is central to the triple helix, is essential if Nigeria is to establish a sustainable aquaculture sector [121]. Public investments that are directed toward academic aquaculture farms and supported by the private sector would increase innovation, skills development, and technology access. This coordinated strategy will allow Nigeria to build a globally competitive aquaculture system that supports food security, inclusive development, ecological balance, and economic growth [13,15].

6. Technological Innovation and Progress in Nigeria's Aquaculture Sector

Technological innovation is gradually transforming Nigeria's aquaculture industry, with RAS being introduced as a method that improves water quality, minimizes disease risk, and enables higher stocking densities through closed-loop water recycling [122]. Although their potential has been acknowledged, RAS has only been adopted by an estimated 10–15% of farms, mainly due to the high initial investment and the technical expertise that is required for proper operation. Moreover, their sustainability depends on energy source and waste handling. Therefore, in areas with highly unstable and diesel-dependent power, improved earthen pond systems with optimized feed, biosecurity, and effluent management may be more sustainable and cost-effective than diesel-backed RAS, making its adoption a context-dependent option rather than a universal solution in the Nigerian situation [123,124]. Where RAS has been implemented successfully, significant improvements have been achieved in fish growth, production efficiency, and environmental impact, which confirms its suitability for scaling high-value aquaculture operations [123]. Additionally, innovation in fish feed technology is progressing, as new efforts have been made to develop farm-made pellets and utilize agro-industrial by-products in feed formulation [125].

One notable development that is gaining attention is the use of microbiome-enhanced feeds, which contain beneficial microbes that have been shown to improve nutrient uptake and digestion, supporting fish health and improving growth [126]. These microbial additives have been shown to enhance survival and growth by 35–54% and reduce the need for antibiotics, an essential step in combating antimicrobial resistance (AMR), a persistent threat to sustainable aquaculture [127,128]. The expansion of Nigeria's fish processing industry is also required if it is to match countries such as Thailand, which is recognized for its diverse fish products and advanced processing technologies [129,130]. Nigeria's current reliance on traditional drying and smoking methods could be reduced by investing in value-added options such as ready-to-eat fish meals, seasoned fillets, protein snacks, and other processed products. Processing innovations, such as vacuum sealing, canning, and filleting, should be promoted because they can increase product shelf life, quality, and market access. For these changes to be implemented widely, infrastructure and skill development must be prioritized for small- and medium-sized enterprises that operate in the aquaculture value chain. Moreover, a phased upgrading pathway is proposed to improve aquaculture processing among SMEs while balancing cost and value. Phase 1 focuses on basic improvements such as hygienic handling, smoking, drying, and simple packaging. Phase 2 introduces moderate upgrades like cold storage, filleting, packaging, and branding through cooperative or leasing models. Phase 3 advances to high value-added processing such as freezing, canning, and certification, supported by stronger market linkages and financing. Implementation should leverage concessional loans, equipment leasing, cooper-

ative guarantees, and incubation through universities or public–private pilot hubs offering shared cold chain facilities [131]. In addition, specialized breeding consultancy services are essential, as they provide technical support for gene banking, selective breeding, and the development of genetically improved strains. These services help to align breeding objectives with technological upgrades to improve the genetic performance and adaptability of farmed fish [132]. Expanding these innovations will depend on coordinated investments that are directed toward technology adoption and the development of a trained workforce. This will also require comprehensive extension services and technical education programs that can distribute knowledge across the sector. The triple helix model, which promotes collaboration between academic institutions, government bodies, and private firms, should be used to strengthen research, attract funding, and ensure efficient technology transfer [13]. This type of institutional partnership enhances capacity, stimulates innovation, and supports the productivity and sustainability of the aquaculture industry. When technologies such as RAS, microbiome-based feeds, advanced food processing systems, and breeding consultancy are integrated strategically, aquaculture systems in Nigeria can be modernized effectively [123,124]. By adopting these innovations and aligning them with national development goals, Nigeria can improve its aquaculture output, ensure environmental protection, and build a more resilient and competitive economy [13,124]. These efforts will allow Nigeria to move toward greater food security, self-sufficiency, and international market leadership.

7. Ecological and Sustainability Issues

The rapid expansion that has occurred in Nigeria's aquaculture industry has been associated with ecological challenges that may threaten the long-term sustainability of the sector and the health of surrounding ecosystems. One critical issue that has been observed is the over-fishing of wild fish populations, especially of species such as *Heterobranchus* and *Clarias*, which have been reported to decline by approximately 20–30% over the last decade in several regions, especially within the Niger Delta and other coastal zones [133–135]. This depletion has been exacerbated by unregulated and illegal harvesting activities, which have placed severe pressure on natural stocks and posed risks to the biodiversity, ecological stability, and resilience of native aquatic ecosystems [136]. The persistent removal of wild stocks, which has not been accompanied by proper management or replenishment measures, has degraded the ecological base upon which many communities and ecosystems depend. In addition, environmental degradation through water pollution, eutrophication, and habitat destruction has been intensified by intensive pond and cage aquaculture systems that have not been properly managed [137].

Excess feed, uneaten waste, and fish excretions contribute to nutrient build-up in water bodies, which can lead to algal blooms, oxygen depletion, and the subsequent mortality of aquatic species [138]. Poorly secured farm infrastructure often causes habitat encroachment, which causes the erosion of wetlands and the destruction of vital riparian zones. These effects have further weakened ecological integrity in areas such as the Niger Delta, which have already been impacted by oil exploration, pollution, and land-use change [33,139]. An explicit ecological risk assessment is necessary to manage the potential impacts of *Heteroclarias* escape into natural water bodies. This should involve hazard identification (evaluating the hybrid's survival, reproduction, and competitiveness across ecosystems), exposure assessment (mapping escape routes and proximity to wild populations, particularly in the Niger Delta), and consequence assessment (examining risks of competition, genetic introgression, and disease transmission through controlled trials). Mitigation measures should include the production of sterile seed where feasible, use of closed or double-containment farming systems in high-risk zones, mandatory escape reporting, and rapid response proto-

cols. Hybrid production should be restricted in ecologically sensitive areas, complemented by the long-term monitoring of wild *Clarias* and *Heterobranchus* populations. It has also been suggested by stakeholders that the stronger enforcement of environmental regulations and promotion of habitat conservation are urgently required. Sustainable alternatives such as integrated aquaculture systems, which incorporate wetlands protection, reforestation, and water quality monitoring, have been identified as viable solutions [140]. Techniques such as integrated multi-trophic aquaculture (IMTA), in which different species are cultivated together to utilize resources efficiently, reduce waste, and further mitigate ecological risks, have also been recommended [141,142]. Public education, community participation, and policy reform will be essential for building a sustainable aquaculture sector that protects biodiversity and supports economic growth [143].

8. Export and Market Development

Nigeria's current export performance in the aquaculture sector has been hindered primarily by challenges that are related to product quality, non-compliance with international standards, and the absence of traceability systems [120,144]. Fewer than 10% of exported fish have been able to meet the highest global quality standards that are required by regulators in the EU, U.S., and Asian markets, but the majority have failed to qualify due to inconsistent quality, poor management practices, and lack of proper certification [22]. These limitations have reduced Nigeria's competitiveness in premium international markets and undermined national efforts to expand exports intended to increase export volumes. Strategic investments that focus on several critical areas will be required to achieve a 30–50% increase in export volume within five years. The first of these involves the establishment of internationally accepted certification schemes such as GLOBALG.A.P. and other quality assurance programs that confirm that fish have been farmed responsibly, kept free of contaminants, and handled in ways that meet the safety thresholds [145,146]. These schemes have been known to build consumer confidence and provide access to premium markets. Second, investment in cold chain infrastructure that includes cold storage at processing points, ports, and transit hubs has been identified as essential for the maintenance of fish quality, reduction in spoilage, and assurance of freshness in international shipments [147]. In addition, traceability systems that support transparency and product origin tracking have become increasingly important to international buyers, who expect an assurance of compliance with export standards [148].

Tools such as blockchain, QR codes, and digital platforms are being adopted in other regions for real-time supply chain monitoring and fraud prevention [149]. Furthermore, Nigeria's export capacity can be bolstered if new markets such as North America, Europe, and Asia are accessed, and if product forms are diversified to include not only fresh and frozen fish, but also value-added processed products. High-value niche items, such as specialty fillets, smoked fish, or branded packaged products, can be developed to distinguish Nigerian exports and secure higher prices. However, these goals cannot be achieved unless breeding management and quality control systems, which are currently underdeveloped in Nigeria, are strengthened to produce genetically superior fish that possess consistent quality, size, and safety profiles. Fish uniformity and export acceptance rates can be improved if better breeding methods and farm management are applied. Coordinated improvements across product quality, standard compliance, certification, traceability, and diversification strategies are needed to unlock Nigeria's export potential and support sustainable industry growth.

9. Opportunities and Future Outlook

Nigeria's catfish industry holds tremendous potential for sustainable growth and global competitiveness, provided that targeted strategic interventions are effectively implemented. Productivity and profitability are driven by the continual introduction of new, higher-yielding, pest- and disease-resistant, and climate-resilient fish breeds that align with both the farmers' needs and consumer preferences. This replacement occurs through a continuous cycle, delivering ongoing genetic gains. Therefore, there is an urgent need to develop and provide a pipeline of breeds and products that meet farmer, consumer, and market demands to replace the breeds currently available in production systems. The Crops to End Hunger initiative recognizes that accelerating the development and delivery of new plant varieties requires a range of activities including the development and implementation of formalized "product profiles". One of the key components of a modernization agenda, and a best practice recommended by the Breeding Program Assessment Tool (BPAT), is the systematic use of product profiles, which should be based on continually updated market intelligence and stakeholder consultations. A major opportunity has been identified in the development of large-scale breeding programs, which are expected to focus on hybrid strains such as *Heteroclarias*, which can produce 10 to 15 million high-quality fingerlings annually [11,15].

Such industry demand, which has rapidly increased, is anticipated to be met by these programs through the production of genetically superior, fast-growing, and disease-resistant fish, whose stock consistency and productivity should be enhanced. Human capacity must be significantly strengthened through the training and retention of a new generation of fish breeders and scientists. The evolving dynamics of pests and diseases, climate change, and shifting consumption patterns require fish breeders to develop new breeds that are better adapted to biotic and abiotic stresses across farm and agro-industrial value chains. However, knowledge of the socio-cultural structures linking farmers, middlemen, processors, and consumers of fish remains scarce. The preferences and needs of men and women participating in fish value chains are poorly understood and currently not available to fish breeders. Additionally, knowledge of the many quality traits that influence user preferences, breed utilization, and stakeholder adoption remains highly fragmented. Multidisciplinary teams, combining experts from social sciences and food technology, should conduct coordinated national surveys to capture these critical traits. Additionally, short-term training for breeders and technicians, particularly on new and emerging breeding tools, needs to be implemented. Special emphasis should be placed on training breeders in gender issues related to fish production systems. A strategic approach should focus on the sustained capacity strengthening of national agricultural research systems including colleges, research centers, and relevant universities. The formation of a Fish Community of Practice (FCoP) will help create and maintain close links among breeding programs by facilitating the sharing of experiences, methods, mating techniques, best field practices, screening protocols, data, and updates on safe germplasm exchange. The FCoP will organize regular meetings, webinars, seminars, and workshops as well as provide infrastructure support. It will also promote peer performance evaluation and healthy competition among fish breeding programs across the region, ultimately benefiting fish producers and consumers. To ensure that the FCoP functions effectively rather than as a formality, it should operate under a clear governance and incentive framework linked to existing institutions. A small steering committee with representatives from the federal fisheries authority, academia, private hatcheries, farmer groups, civil society, and development partners will provide oversight. It will be supported by a secretariat and technical working groups on breeding, biosecurity, traceability, and processing. Incentives such as access to quality broodstock, subsidized training, technical support, group certification, and

performance-based grants will encourage participation. A formal memoranda of understanding and legal registration as an association or trust would enhance funding access and accountability. Collaboration with the Department of Fisheries, universities, and private hatcheries would strengthen institutional linkages. To avoid tokenism, implementation should be based on time-bound pilot projects with measurable KPIs, transparent reporting, and independent technical oversight. In addition to the aforementioned capacity-building initiatives, efforts should be made to provide comprehensive training to farmers, hatchery operators, and extension agents to improve survival rates, control disease outbreaks, and accelerate fish growth [115,150]. Evidence suggests that these measures alone could boost farm productivity by 50–70% and make the industry more profitable and resilient. Technological adoption also presents a key avenue for expansion [15]. The rate of historical genetic gains indicates that reliance on conventional breeding methods alone is unsustainable for meeting the needs of an increasing human population. Therefore, innovative breeding strategies are required to accelerate genetic gains [151].

Developing an accurate predictive platform to assess performance can significantly shorten the breeding cycle and enhance the rate of progress, making it a strategic approach for achieving higher genetic gains. The application of RAS, automated feeding technologies, and water quality monitoring tools should be employed to enhance production efficiency, reduce environmental impacts, and improve product quality, which are essential for gaining international market access [152–154]. Food processing innovation, which has been inspired by models from countries such as Thailand, can support the creation of diverse product lines, value-added processing, and eco-friendly packaging, which could allow Nigeria to access higher-value markets domestically and internationally. Strengthened regulatory frameworks and robust certification schemes, such as GLOBALG.A.P. or ISO, should be established to ensure compliance and reassure global buyers and possibly increase export volumes [155]. To improve market access while considering SME capacity, a national aquaculture standard for Nigeria is proposed as a tiered, risk-based system. The basic tier would focus on food safety and hygiene for local trade, the intermediate tier would align with regional and export requirements, and the advanced tier would correspond to international standards such as GLOBALG.A.P. Group certification, cooperative models, and subsidized audits would help reduce compliance costs, creating an affordable and locally relevant pathway to higher-value markets. These measures are expected to support conformity with international food safety requirements, reduce rejection rates, and unlock new market opportunities. Increased efforts should be made to develop an open-access data management platform for managing and sharing fish breeding data, thereby facilitating collaboration and knowledge exchange. The database will support the integration of breeding data collected and generated over the years within the FCoP. It will also enable trial creation, assist in diversity management, and facilitate the integration of phenotypic and genomic data.

The future growth of Nigeria's aquaculture sector will depend on strong collaboration among government, private industry, academia, and international development partners through a triple helix model. To reduce the risk of bureaucratic inertia or rent-seeking, there is a need for transparent MoUs with explicit deliverables, the inclusion of farmer and processor representatives in governance bodies, performance-based funding tied to measurable outcomes, independent external evaluations, and pilot projects with sunset clauses. Case studies, including university-led incubation and industry collaborations in Thailand, Vietnam and Namibia, provide replicable models for aligning academic research with practical needs and building farm-facing extension capacity [117,118,129,130]. Public–private partnerships should be mobilized to develop infrastructure, foster research and development, facilitate technology transfer, and scale capacity building. Growth must also

be aligned with ecological safeguards such as habitat conservation, pollution management, and genetic integrity assurance [11]. If these approaches are implemented strategically, Nigeria may be positioned as a global leader in sustainable catfish production and supply. Considerable progress has been recorded over the last two decades, and with innovation, institutional reform, and sustainable practices, full industry potential can be realized.

10. Conclusions

Nigeria's catfish industry has significant potential to achieve self-sufficiency and global competitiveness, but this requires strategic and coordinated action. Key priorities include establishing a functional FCoP to harmonize breeding and germplasm management, expanding certified hatchery capacity to meet the national demand for quality seed, and implementing data-driven genetic improvement programs to enhance productivity. In addition, scaling recirculating aquaculture systems (RASs), strengthening feed and processing value chains, and adapting international certification and traceability standards in line with local realities will improve the product quality and export potential. A focused, time-bound roadmap integrating research, policy, and industry collaboration will be critical to transforming the Nigerian catfish sector into a resilient and sustainable aquaculture model.

Author Contributions: Conceptualization, K.S. and T.P.; Methodology, A.C.; Validation, W.S., U.U., U.E. and J.E.O.; Investigation, T.P.; Data curation, J.P.; Writing—original draft preparation, K.S. and T.P.; Writing—review and editing, K.S., T.P., W.S., U.U., U.E. and J.E.O.; Supervision, K.S.; Project administration, K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was granted by the Program Management Unit for Competitiveness (PMU-C) under the Global Partnership Program (Contract No. C23F670224), awarded to WS, TP, JP, and KS; the National Research Council of Thailand: High-Potential Research Team Grant Program (N42A660605) awarded to KS, TP, AC, JP, and WS; the Program Management Unit for Human Resources and Institutional Development and Innovation (PMU-B) (Contract No. B13F670053), awarded to WS, TP, JP, and KS; the Program Management Unit on Area Based Development (PMU-A) (Contract No. A11F680039) awarded to WS, TP, AC, JP, and KS; a grant from Kasetsart University Research and Development Institute (FF (KU)25.64, FF (S-KU)17.66, and FF (KU)51.67) awarded to WS and KS; the Postdoctoral Fellowship from Kasetsart University (Contract No. 6501.2107/160) awarded to TP; and support from the International SciKU Branding (ISB), Faculty of Science, Kasetsart University awarded to WS and KS. No funding source was involved in the study design, collection, analysis, and interpretation of the data, writing of the report, or decision to submit the article for publication.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to express our deepest gratitude to the Federal Cooperative College Oji River, Enugu State, Nigeria. We also sincerely thank the Faculty of Science, Kasetsart University (6501.0901.1/336).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rocha, C.P.; Cabral, H.N.; Marques, J.C.; Gonçalves, A.M. A global overview of aquaculture food production with a focus on the activity's development in transitional systems—The case study of a South European Country (Portugal). *J. Mar. Sci. Eng.* **2022**, *10*, 417. [CrossRef]
2. Subasinghe, R.; Siriwardena, S.N.; Byrd, K.; Chan, C.Y.; Dizyee, K.; Shikuku, K.; Tran, N.; Adegoke, A.; Adeleke, M.; Anastasiou, K.; et al. *Nigeria Fish Futures: Aquaculture in Nigeria—Increasing Income, Diversifying Diets and Empowering Women*; The WorldFish Center: Penang, Malaysia, 2021.

3. Walakira, J.K.; Hinrichsen, E.; Tarus, V.; Langi, S.; Ibrahim, N.A.; Badmus, O.; Aziz, A.; Baumüller, H. *Scaling Aquaculture for Food Security and Employment in Africa: Insights from Egypt, Kenya and Nigeria*; ZEF Working Paper No. 223; Center for Development Research, University Bonn: Bonn, Germany, 2023; Available online: https://hdl.handle.net/10419/278612 (accessed on 25 August 2025).
4. Bartley, D.M. *World Aquaculture 2020—A Brief Overview*; FAO Fisheries and Aquaculture Circular No. 1233; FAO: Rome, Italy, 2022. [CrossRef]
5. Dewali, S.; Sharma, N.; Melkani, D.; Arya, M.; Kathayat, N.; Panda, A.K.; Bisht, S.S. Aquaculture: Contributions to global food security. In *Emerging Solutions in Sustainable Food and Nutrition Security*; Springer: Cham, Switzerland, 2023; pp. 123–139. [CrossRef]
6. Atawodi, J.C.; Abovegodwin, G.O.; Ngwamah, J.S.; Ugwoke, V.E. A critical review of fish production dynamics and sustainability in Nigeria. *Conflu. J. Pure Appl. Sci.* **2025**, *4*, 69–81.
7. Samuel, O.O. Involvement in Fish Farming and the Wellbeing of Youths in Southwestern Nigeria. Ph.D. Thesis, University of Ibadan, Ibadan, Nigeria, 2021. Available online: http://hdl.handle.net/123456789/1426 (accessed on 25 August 2025).
8. Atkins, M.; Byrd, K.A.; Pincus, L.; Naziri, D.; Yossa, R.; Thilsted, S.H. *Integrating Fish, Roots, Tubers and Bananas in Food Systems: Opportunities and Constraints*; Working Paper: FISH-2020-06; CGIAR Research Program on Fish Agri-Food Systems & CGIAR Research Program on Roots, Tubers and Bananas: Penang, Malaysia, 2020.
9. Ajayi, O.; Akinrinlola, A.; Usman, A.; Muhammed, A.; Van der Knaap, M. Aquaculture development in Nigeria and FAO's role. *FAO Aquac. Newsl.* **2022**, *65*, 21–24. Available online: https://www.proquest.com/scholarly-journals/aquaculture-development-nigeria-faos-role/docview/2680352926/se-2 (accessed on 25 August 2025).
10. Mapfumo, B. Regional Review on Status and Trends in Aquaculture Development in Sub-Saharan Africa–2020. 2022. Available online: https://www.google.com/books?hl=nl&lr=&id=AsNfEAAAQBAJ&oi=fnd&pg=PR3&dq=Regional+Review+on+Status+and+Trends+in+Aquaculture+Development+in+Sub-Saharan+Africa%E2%80%932020&ots=rJR1RFiLxp&sig=0z8bp6hVKPy8uWS4yXQ7MxYAj-s (accessed on 22 August 2025).
11. Ogunji, J.; Wuertz, S. Aquaculture development in Nigeria: The second biggest aquaculture producer in Africa. *Water* **2023**, *15*, 4224. [CrossRef]
12. FAO. *The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2022. [CrossRef]
13. Olagunju, O.F.; Kristófersson, D.; Tómasson, T.; Kristjánsson, T. Profitability assessment of catfish farming in the Federal Capital Territory of Nigeria. *Aquaculture* **2022**, *555*, 738192. [CrossRef]
14. Akinwole, A.O.; Faturoti, E.O. Biological performance of African catfish (*Clarias gariepinus*) cultured in recirculating system in Ibadan. *Aquac. Eng.* **2007**, *36*, 18–23. [CrossRef]
15. Isa, S.I. Development of Genetic Improvement in the African Catfish (*Clarias gariepinus*, Burchell, 1822). 2019. Available online: http://hdl.handle.net/1893/29986 (accessed on 18 August 2025).
16. Kafumukachemilu, E. Fish Value Chain Dynamics: Livelihood Opportunities and Challenges for Small-Scale Farmers in Lusaka District. 2021. Available online: http://dspace.unza.zm/handle/123456789/7689 (accessed on 25 August 2025).
17. Adeleke, B.; Robertson-Andersson, D.; Moodley, G.; Taylor, S. Aquaculture in Africa: A comparative review of Egypt, Nigeria, and Uganda vis-à-vis South Africa. *Rev. Fish. Sci. Aquac.* **2020**, *29*, 167–197. [CrossRef]
18. Engle, C.; Kumar, G. *Ictalurus punctatus* (Channel Catfish). CABI Compendium Datasheet. 2023. Available online: https://www.cabidigitallibrary.org/doi/abs/10.1079/cabicompendium.79127 (accessed on 10 September 2025).
19. Oluwagbemiga, E.A.; Alabi, J. Nigeria's mono-cultural economy and the African catfish aquaculture industry. In Proceedings of the Covenant University Conference on e-Governance, Ota, Nigeria, 7–9 June 2017.
20. Chan, C.Y.; Chu, L.; Tran, N.; Sarı, E.C.; Cheong, K.C.; Olagunju, O.; Shikuku, K.; Byrd, K.; Kanar, D.; Subasinghe, R.; et al. *Future of Fish for Food and Nutrition Security in Nigeria*; WorldFish Working Paper: 2024-62; WorldFish: Penang, Malaysia, 2024. Available online: https://hdl.handle.net/10568/163446 (accessed on 25 August 2025).
21. Olagunju, O.F.; Kristófersson, D.; Tómasson, T.; Kristjánsson, T. Farm strategies and characteristics influencing profitability in Nigerian catfish aquaculture: Lessons on resilience during economic crisis and COVID-type shock. *J. World Aquacult. Soc.* **2024**, *55*, e13058. [CrossRef]
22. FAO. *Aquaculture Growth Potential in Western Africa: WAPI Factsheet to Facilitate Evidence-Based Policy Making and Sector Management in Aquaculture*; FAO: Rome, Italy, 2023.
23. FAO. *Nigeria Catfish Value Chain Analysis*; FISH4ACP Prog.; Food & Agriculture Organization: Rome, Italy, 2021.
24. Areola, F.O.; Osanyinlusi, O.I.; Alatise, O.M.; Oladele, O.O. Implications of Inbreeding in Clarias Gariepinus Fish Farming: Farmers' Perspectives in Nigeria. *J. Aqua. Mar. Bio Ecol.* **2024**, *124*, 1–5. [CrossRef]
25. Fregene, B.T.; Bolorunduro, P.; Yossa, R.; Karisa, H.C.; Olaniyi, A.; Ajose, I. Extension manual on production of quality catfish seed. *Gates Open Res.* **2024**, *8*, 68. [CrossRef]

26. Akintayo, I.A. *Assessing the Feasibility of a Selective Breeding Programme for African Catfish in Nigeria (Final Project)*; GRÓ Fisheries Training Programme, UNESCO: Reykjavík, Iceland, 2022. Available online: https://www.grocentre.is/static/gro/publication/1726/document/Akintayo21prf.pdf (accessed on 25 August 2025).
27. Sanda, M.K.; Metcalfe, N.B.; Mable, B.K. The potential impact of aquaculture on the genetic diversity and conservation of wild fish in sub-Saharan Africa. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **2024**, *34*, e4105. [CrossRef]
28. Khor, L.; Bodunde, O.A.; Wills, R.; Hanson, L.; Adeyemo, O.K.; Aina, O.O.; Chadag, V.M. Understanding aquaculture biosecurity to improve catfish disease management in Ogun and Delta states, Nigeria. *Aquaculture* **2024**, *584*, 740664. [CrossRef]
29. Ogello, E.; Schindler, L.; Chan, C.Y.; Tran, N.; Obiero, K.; Outa, N.; Muthoka, M.; Kyule, D.; Atieno, V. *Exploring Future Scenarios for Advancing Low-Emission Development in Kenyan Aquatic Food Systems*; WorldFish Working Paper: 2024-63; WorldFish: Penang, Malaysia, 2024.
30. Anetekhai, M.A. *Catfish Aquaculture Industry Assessment in Nigeria (Tech. Rep.)*; Lagos State University: Lagos, NA, USA, 2017. [CrossRef]
31. Olagunju, O.F.; Kristófersson, D.; Kristjánsson, T.; Tómasson, T. Technical efficiency of African catfish production in Nigeria: An analysis involving input quality and COVID-19 effects. *Aquac. Econ. Manag.* **2023**, *28*, 1–27. [CrossRef]
32. Kaleem, O.; Sabi, A.-F.B.S. Overview of aquaculture systems in Egypt and Nigeria: Prospects, potentials, and constraints. *Aquacult. Fish.* **2021**, *6*, 535–547. [CrossRef]
33. ReportLinker. Nigeria Aquaculture Market Report: Trends, Forecasts, and Statistics. 2023. Available online: https://www.reportlinker.com/ (accessed on 25 August 2025).
34. FAO. *Cultured Aquatic Species Information Programme. Clarias gariepinus*; FAO Fisheries Aquacult. Dep.: Rome, Italy, 2024. Available online: https://www.fao.org/fishery/en/culturedspecies/clarias_gariepinus/en (accessed on 25 August 2025).
35. Tan, N.D.; Tuyen, V.T.X.; Ha, H.T.N.; Dao, D.T.A. Overview: The value chain of tra catfish in Mekong Delta region, Vietnam. *Vietnam J. Chem.* **2023**, *61*, 1–14. [CrossRef]
36. Cocker, L.M. *Strategic Review on African Aquaculture Markets and Export Potential*; Partnership for African Fisheries (PAF) Aquaculture Working Group, University of Stirling/NEPAD Report; Institute of Aquaculture, University of Stirling: Stirling, UK, 2014.
37. Adeyeye, S.A.O. Traditional fish processing in Nigeria: A critical review. *Nutr. Food Sci.* **2016**, *46*, 321–335. [CrossRef]
38. Clearinghouse, T.A.A.T. *Aquaculture Technology Toolkit Catalogue*; Clearinghouse Technical Report Series No. 012; Technologies for African Agricultural Transformation, Clearinghouse Office, IITA: Nairobi, Kenya, 2022.
39. Adebayor, F.T. A survey of fish sold in Liverpool market in Lagos. *Afr. J. Trop. Agric.* **2014**, *2*, 93–97.
40. Akintola, S.L.; Fakoya, K.A. Small-scale fisheries in the context of traditional post-harvest practice and the quest for food and nutritional security in Nigeria. *Agric. Food Secur.* **2017**, *6*, 34. [CrossRef]
41. Abdullahi, S.A.; Shuaibu, S. Marketing of smoked fish in Kano State, Nigeria. *Bayero J. Pure Appl. Sci.* **2013**, *6*, 120–125.
42. Ewumi, A.F.; Rahman, M.A.; Sarfo, I.; Darko, G.; Olowe, O.S. Catfish farming: A sustainability study at Eriwe fish farming village in southwest Nigeria. *Aquacult. Int.* **2021**, *29*, 1619–1631. [CrossRef]
43. Osundare, F.; Adedeji, T. Economic analysis of market performance of fresh fish in Lagos State, Nigeria. *Int. J. Environ. Agric. Biotechnol.* **2018**, *3*, 594–599. [CrossRef]
44. Sobczak, M.; Panicz, R.; Sadowski, J.; Półgęsek, M.; Żochowska-Kujawska, J. Does production of *Clarias gariepinus* × *Heterobranchus longifilis* hybrids influence quality attributes of fillets? *Foods* **2022**, *11*, 2074. [CrossRef]
45. Abit, L.Y.; Mojilis, M.; Latif, K.; Al-Asif, A. Successful hybridization between *Clarias microstomus* ♂ and *Clarias gariepinus* ♀. *AACL Bioflux* **2023**, *16*, 3285–3295.
46. Rahman, M.A.; Lee, S.G.; Yusoff, F.M.; Rafiquzzaman, S.M. Hybridization and its application in aquaculture. In *Sex Control in Aquaculture*; Wiley: Hoboken, NJ, USA, 2018; pp. 163–178. [CrossRef]
47. Adewumi, A.A.; Olaleye, V.F. Catfish culture in Nigeria: Progress, prospects and problems. *Afr. J. Agric. Res.* **2011**, *6*, 1281–1285. [CrossRef]
48. Ayele, T.A. Growth Performance and Survival Rate of African Catfish Larvae *Clarias gariepinus* (Burchell 1822) Fed on Different Types of Live and Formulated Feeds. Master's Thesis, University of Natural Resources and Life Sciences, Vienna, Austria, 2015.
49. Barasa, J.E.; Ouma, D.F. Towards sustainability in seed supply for African catfish, *Clarias gariepinus* (Burchell, 1822) culture in Kenya: Lessons from the Asian catfish industry. *Aquac. Res.* **2024**, 1341858. [CrossRef]
50. Uche, C.G.; Aga, T.; Ulasi, G.F. Review on status of African catfish aquaculture in Nigeria. *Int. J. Latest Technol. Eng. Manag. Appl. Sci.* **2023**, *12*, 102–111. [CrossRef]
51. Oman, S.; Kapaipi, M.; Hodzic, H.; Megahed, M. *The Catfish Aquaculture Value Chain in Nigeria: Analysis and Design Report*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2023.
52. Oyebola, O.O.; Olatunde, O.M. Climate change adaptation through aquaculture: Ecological considerations and regulatory requirements for tropical Africa. In *Agriculture and Ecosystem Resilience in Sub-Saharan Africa*; Bamutaze, Y., Kyamanywa, S., Singh, B., Nabanoga, G., Lal, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2019. [CrossRef]

53. Collins, R.; Dent, B. *A Manual for Agribusiness Value Chain Analysis in Developing Countries*; Tech. Rep. No. 20210424166; CABI: Wallingford, UK, 2021.
54. Oboh, A. Diversification of farmed fish species: A means to increase aquaculture production in Nigeria. *Rev. Aquacult.* **2022**, *14*, 2089–2098. [CrossRef]
55. Adesina, S.A.; Agbatan, O.D. Growth response and feed utilization in *Clarias gariepinus* fingerlings fed diets supplemented with processed flamboyant (*Delonix regia*) leaf meal. *Agro-Sci. J. Trop. Agric. Food Environ. Ext.* **2021**, *20*, 38–45. [CrossRef]
56. Hasan, M.R.; New, M.B. On-Farm Feeding and Feed Management in Aquaculture. FAO Fisheries and Aquaculture Technical Paper, (583), I, III, IV, VIII, IX, X, 1, 3-67. 2013. Available online: https://www.proquest.com/scholarly-journals/on-farm-feeding-feed-management-aquaculture/docview/1496068411/se-2 (accessed on 25 August 2025).
57. Sanda, M.K.; Metcalfe, N.B.; Capstick, M.; Mable, B.K. Genetic diversity, population structure and differentiation of farmed and wild African catfish (*Clarias gariepinus*) in Nigeria. *bioRxiv.* **2024**. [CrossRef]
58. Akin-Obasola, B.J.; Fapohunda, O.O.; Ogunlade, A.O. Comparative study of growth performance, nutritional composition and gonadal development of *Heteroclarias* cultured in concrete and earthen ponds. *Ekiti State Univ. J. Sci. Technol.* **2022**, *7*, 49–56.
59. Ayanwale, A.V.; Mohammed, Y.M.; Adama, S.B.; Ajayi, T.R. Different stocking density levels on some growth parameters and survival of *Heteroclarias* fingerlings reared under laboratory conditions in Minna, Niger State. *Dutse J. Pure Appl. Sci.* **2020**, *6*, 69–78.
60. Oluwashina, M.M.; Solomon, R.J. Comparative study of feed utilization and growth performance in Heteroclarias. *Research* **2012**, *4*, 45–54.
61. Ajah, P.O.; Edeghe, A.I.; Enin, U.I. Growth of *Clarias gariepinus* reared in earthen ponds in Calabar, South-South, Nigeria under duo nutritional diet. *J. Aquac. Fish.* **2022**, *6*, 2. [CrossRef]
62. Owodeinde, F.G.; Fakoya, K.; Anetekhai, M.A. Growth performance of hybrid catfish (*Clarias gariepinus* × *Heterobranchus bidorsalis*) in earthen ponds. *Asian J. Biol. Sci.* **2012**, *5*, 192–200. [CrossRef]
63. FAO. *Fishery and Aquaculture Country Profiles: Nigeria 2024*; Country Profile Fact Sheet; Fisheries and Aquaculture Division: Rome, Italy, 2025. Available online: https://www.fao.org/fishery/en/facp/nga (accessed on 21 July 2025).
64. Olutumise, A.I.; Adene, I.C.; Ajibefun, A.I.; Amos, T.T. Adoption of improved technologies and profitability of the catfish processors in Ondo State, Nigeria: A Cragg's double-hurdle model approach. *Sci. Afr.* **2020**, *10*, e00576. [CrossRef]
65. FAO. *Report of the FAO Expert Workshop on the Use of Wild Fish and/or Other Aquatic Species as Feed in Aquaculture and Its Implications to Food Security and Poverty Alleviation*; FAO Fish. Rep. No. 867; FAO: Rome, Italy, 2008.
66. Negari, B.; Yusuf, Y.; Hundie, D.; Ameha, N.; Kebede, K.; Abrar, B.; Diba, D. A comparison of growth performance, feed intake, and feed efficiency of broiler chickens fed on commercial and farm-formulated diets. *East Afr. J. Vet. Anim. Sci.* **2024**, *8*, 27–34. [CrossRef]
67. Ossai, N.I.; Eneje, V.O.; Andong, F.A.; Enyi, K.M.; Nnachetam, R.C.; Orji, E.A.; Eyo, J.E. Studies on the genetic improvement of the African catfish (*Clarias gariepinus* Burchell, 1822) by triploidy. *Anim. Res. Int.* **2024**, *21*, 5503–5517.
68. Project Championz. Survival and growth rate of *Heterobranchus longifilis* induced with Ovaprim and pituitary extract of *H. longifilis*. 2017. Available online: https://projectchampionz.com.ng/ (accessed on 24 August 2025).
69. Kwikiriza, G.; Tebitendwa, S.M.; Rwezawula, P.; Mwanja, W.W.; Abaho, I.; Meimberg, H. Enhancing African catfish (*Clarias gariepinus*) aquaculture in Uganda: Insights into hatchery propagation, population suitability, and broodstock management. *Fishes* **2025**, *10*, 290. [CrossRef]
70. Lind, C.E.; Ponzoni, R.W.; Nguyen, N.H.; Khaw, H.L. Selective breeding in fish and conservation of genetic resources for aquaculture. *Reprod. Domest. Anim.* **2012**, *47*, 255–263. [CrossRef]
71. Hilsdorf, A.W.; Hallerman, E.M. *Genetic Resources of Neotropical Fishes*; Springer: Cham, Switzerland, 2017. [CrossRef]
72. Wachirachaikarn, A.; Na-Nakorn, U. Genetic diversity of the North African catfish, *Clarias gariepinus* (Burchell, 1822) hatchery stocks in Thailand. *ScienceAsia* **2019**, *45*, 301–308. [CrossRef]
73. Sankaran, G.B.; Mandal, A. Genetic improvements in aquaculture. *Trout J. Atatürk Univ.* **2024**, *2*, 16–25. [CrossRef]
74. Casillas, S.; Barbadilla, A. Molecular population genetics. *Genetics* **2017**, *205*, 1003–1035. [CrossRef] [PubMed]
75. Myers, J.N. Analysis of Gamete Interactions, Maternal, and Paternal Effects for Improving Hybrid CATFISH Aquaculture (Order No. 30263049). 2019. Available from ProQuest One Academic. (2779137434). Available online: https://www.proquest.com/dissertations-theses/analysis-gamete-interactions-maternal-paternal/docview/2779137434/se-2 (accessed on 25 August 2025).
76. Collard, B.C.; Mackill, D.J. Marker-assisted selection: An approach for precision plant breeding in the twenty-first century. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **2008**, *363*, 557–572. [CrossRef] [PubMed]
77. Yue, G.H. Recent advances of genome mapping and marker-assisted selection in aquaculture. *Fish Fish.* **2014**, *15*, 376–396. [CrossRef]
78. Ponzoni, R.W.; Nguyen, N.H. (Eds.) *Proceedings of a Workshop on the Development of a Genetic Improvement Program for African Catfish Clarias gariepinus*; WorldFish Center Conf. Proc. No. 1889; The WorldFish Center: Penang, Malaysia, 2008. Available online: https://cabidigitallibrary.org/terms-and-conditions (accessed on 24 August 2025).

79. Chattopadhyay, N.R. *Induced Fish Breeding: A Practical Guide for Hatcheries*; Academic Press: Cambridge, MA, USA, 2016.
80. Sucipto, A.; Muhammad, R. *Seed Production of Catfish in Biofloc*; Akuatika Indonesia Raya: West Java, Indonesia, 2024.
81. Ingram, B.A.; Nguyen, T.T.T. Broodstock management and breeding in relation to culture-based fisheries. In Proceedings of the Regional Consultation on Culture-Based Fisheries Development in Asia, Siem Reap, Cambodia, 21–23 October 2014.
82. Coogan, M.P. Genetic Technologies for Growth Enhancement in Catfish. Ph.D. Thesis, Auburn University, Auburn, Alabama, 2021.
83. Patta, C.; Panthum, T.; Thatukan, C.; Wongloet, W.; Chalermwong, P.; Wattanadilokchatkun, P. Questioning inbreeding: Could outbreeding affect productivity in the North African catfish in Thailand? *PLoS ONE* **2024**, *19*, e0302584. [CrossRef]
84. Senanan, W.; Kapuscinski, A.R.; Na-Nakorn, U.; Miller, L.M. Genetic impacts of hybrid catfish farming (*Clarias macrocephalus* × *C. gariepinus*) on native catfish populations in central Thailand. *Aquaculture* **2004**, *235*, 167–184. [CrossRef]
85. Kwikiriza, G.; Abaho, I.; Tibihika, P.D.; Izaara, A.A.; Atukwatse, F.; Omara, T.; Nattabi, J.K.; Kasozi, N.; Curto, M.; Melcher, A.; et al. Genetic Diversity and Population Differentiation of Farmed Nile Tilapia (*Oreochromis niloticus* Linnaeus, 1758) to Advance Selective Breeding in Uganda. *Diversity* **2025**, *17*, 128. [CrossRef]
86. Bassey, H. Phenotypic and Genetic Evaluation of Farmed and Wild Clarias Gariepinus Broodstocks in Nigeria (Final Project Report). UNESCO GRÓ—Fisheries Training Programme, Iceland. 2020. Available online: https://www.grocentre.is/static/gro/publication/697/document/Happiness19prf.pdf (accessed on 23 August 2025).
87. Oyebola, O.O. Assessment of Genetic Structure of *Clarias gariepinus* (Burchell, 1822) Population in Asejire Lake. Ph.D. Thesis, University of Ibadan, Ibadan, Nigeria, 2014.
88. Ashley-Dejo, S.; Adelaja, O.A. Economics of catfish hatchery farmers and its contribution to household poverty alleviation in Nigeria. *Agric. Trop. Subtrop.* **2022**, *55*, 19–29. [CrossRef]
89. Ibiwoye, Y.E.; Thorarensen, H. Assessment of broodstock management practices in Nigeria. *Int. J. Innov. Res. Dev.* **2018**, *7*, 198–205. [CrossRef]
90. Teka, M. Factors of Fish Farming Productivity and Sustainability; the Case of Africa Sustainable Aquaculture bv Ethiopian Branch. Ph.D. Thesis, St. Mary's University, San Antonio, TX, USA, 2020. Available online: http://www.repository.smuc.edu.et/bitstream/123456789/5540/1/MEKDES%20TEKA.pdf (accessed on 25 August 2025).
91. Jordan, N.R.; Slotterback, C.S.; Cadieux, K.V.; Mulla, D.J.; Pitt, D.G.; Olabisi, L.S.; Kim, J.O. TMDL implementation in agricultural landscapes: A communicative and systemic approach. *Environ. Manag.* **2011**, *48*, 1–12. [CrossRef]
92. Olesen, I.; Gjedrem, T.; Bentsen, H.Á.; Gjerde, B.; Rye, M. Breeding programs for sustainable aquaculture. *J. Appl. Aquac.* **2023**, *13*, 179–204. [CrossRef]
93. Ansa, E.J. *Challenges and Production Process of Catfish Hatcheries in the Niger Delta Region of Nigeria*; Technical Report No. DAIvbg_1_WGA; Development Alternatives Inc.: Bethesda, MD, USA, 2014. [CrossRef]
94. Mbokane, E.M.; Mbokane, L.M.; Motimele, S.S.; Hlophe-Ginindza, S.N. Successes and challenges of catfish farming in the small-scale industry in Southern Africa. In *Catfish: Advances, Technology, Experiments*; Atamanalp, M., Ed.; IntechOpen: London, UK, 2022. [CrossRef]
95. Katampe, B. The contribution of aquaculture to poverty alleviation/food security among the rural poor in the Federal Capital Territory (FCT) Abuja, Nigeria. Ph.D Thesis, University of Northampton, Northampton, UK, 2023.
96. Oyieng, P.E. Characterization of Smallholder Aquaculture Systems and Growth Performance of the African Catfish (Clarias gariepinus) in High Altitude Areas of Kenya. Ph.D. Thesis, Egerton University, Nakuru, Kenya, 2014.
97. Assefa, A.; Abunna, F. Maintenance of fish health in aquaculture: Review of epidemiological approaches for prevention and control of infectious disease of fish. *Vet. Med. Int.* **2018**, *2018*, 5432497. [CrossRef]
98. Dimelu, M.; Ifeonu, C.F.; Asaduchie, A.N.; Ayogu, B.J. Challenges of disease management in small scale fish farms in Lagos State, Nigeria. *J. Agric. Ext.* **2018**, *22*, 28–41.
99. Mukaila, R.; Ukwuaba, I.C.; Umaru, I.I. Economic impact of disease on small-scale catfish farms in Nigeria. *Aquaculture* **2023**, *575*, 739773. [CrossRef]
100. Akpalu, W.; Nnaemeka, C. A comparative assessment of economic, social, and environmental performance of tilapia aquaculture in Nigeria and Ghana. *Aquac. Econ. Manag.* **2025**, *29*, 159–179. [CrossRef]
101. Waite, R.; Beveridge, M.; Brummett, R.; Castine, S.; Chaiyawannakarn, N.; Kaushik, S.; Mungkung, R.; Nawapakpilai, S.U.P.A.W.A.T.; Phillips, M.I.C.H.A.E.L. *Improving Productivity and Environmental Performance of Aquaculture*; WorldFish: Penang, Malaysia, 2014.
102. Audu, R.; Yola, I.A. Contemporary issues in fisheries and aquaculture: A review on non–conventional feed ingredients for fish feed in Nigeria. *Bayero J. Pure Appl. Sci.* **2021**, *13*, 22–28. [CrossRef]
103. Oguguah, N.M.; Eyo, J.E. Finfish feed technology in Nigeria. *J. Res. Biosci.* **2007**, *3*, 1–17.
104. Piate, R.C.; Orok, U.N. Fish farming: Assessing the process and economic benefits of establishing subsistent and commercial farming. *KING-UK Int. J. Acad. Anthol.* **2024**, *8*, 1–18.
105. Menezes, A.; Ligeon, C.; Murekezi, P.; Jolly, C. *Diagnosis of Aquaculture Employment Governance in Selected African Countries*; FAO Fisheries and Aquaculture Technical Paper, No. 715; FAO: Rome, Italy, 2024. [CrossRef]

106. Digun-Aweto, O.; Oladele, A.H. Constraints to adoption of improved hatchery management practices among catfish farmers in Lagos State. *J. Cent. Eur. Agric.* **2017**, *18*, 841–850. [CrossRef]
107. Joscelyne, M. The Influence of Aquahatch on the Growth Performance of Larval and Juvenile African Catfish (*Clarias gariepinus*, Burchell 1822). 2020. Available online: http://hdl.handle.net/10019.1/107968 (accessed on 25 August 2025).
108. Liverpool-Tasie, L.S.O.; Wineman, A.; Amadi, M.U.; Gona, A.; Emenekwe, C.C.; Fang, M.; Belton, B. Rapid transformation in aquatic food value chains in three Nigerian states. *Front. Aquacult.* **2024**, *3*, 1302100. [CrossRef]
109. Mbiuki, W.N. Relationship Between Fish Farming Enterprise Productivity Training Programme and Adoption of Inland-Based Pond Fish Farming in Meru South Sub-County, Kenya. Ph.D. Thesis, Egerton University, Njoro, Kenya, 2019.
110. Aly, S.M.; Fathi, M. Advancing aquaculture biosecurity: A scientometric analysis and future outlook for disease prevention and environmental sustainability. *Aquacult. Int.* **2024**, *32*, 8763–8789. [CrossRef]
111. Anikwe, S.O.; Unachukwu, L.C.; Onah, F.N. Human capacity development and sustainable growth in the blue economy: Opportunities, challenges, and strategies for Nigeria. *Afr. Bank. Finance Rev. J.* **2024**, *15*, 202–212.
112. Kaminski, A.M.; Kruijssen, F.; Cole, S.M.; Beveridge, M.C.; Dawson, C.; Mohan, C.V.; Suri, S.; Karim, M.; Chen, O.L.; Phillips, M.J.; et al. A review of inclusive business models and their application in aquaculture development. *Rev. Aquacult.* **2020**, *12*, 1881–1902. [CrossRef]
113. Ababouch, L.; Nguyen, K.A.T.; Castro de Souza, M.; Fernández-Polanco, J. Value chains and market access for aquaculture products. *J. World Aquac. Soc.* **2023**, *54*, 527–553. [CrossRef]
114. Ateweberhan, M.; Hudson, J.; Rougier, A.; Jiddawi, N.S.; Msuya, F.E.; Stead, S.M.; Harris, A. Community-based aquaculture in the western Indian Ocean: Challenges and opportunities for developing sustainable coastal livelihoods. *Ecol. Soc.* **2018**, *23*, 34. [CrossRef]
115. Hasan, M.R.; Bueno, P.B.; Corner, R.A. Strengthening, empowering and sustaining small-scale aquaculture farmers' associations. *FAO Fish. Aquacult. Tech. Pap.* **2020**, *655*, I-181. [CrossRef]
116. Lakra, W.S.; Krishnani, K.K. Circular bioeconomy for stress-resilient fisheries and aquaculture. In *Biomass, Biofuels, Biochemicals*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 481–516. [CrossRef]
117. Critchley, A.T.; Molloy, F.J.; van Harmelen, J.D.; Mshigeni, K.E. A strategy for appropriate technology for development in Namibia–recent University of Namibia initiatives: Selected examples and call for collaboration. Pop.–Dev.–Environ. Namibia. 2000, p. 203. Available online: https://core.ac.uk/download/pdf/33897684.pdf#page=220 (accessed on 25 August 2025).
118. Hoang, T. The Contribution of Tertiary Education to Sustainable Economic Development: Evidence from the Seafood Industry in Vietnam. 2023. Available online: https://researchers.cdu.edu.au/files/99475868/Thesis_CDU_Hoang_T_H.pdf (accessed on 23 August 2025).
119. Brugère, C.; Aguilar-Manjarrez, J.; Beveridge, M.C.M.; Soto, D. The ecosystem approach to aquaculture 10 years on—A critical review and consideration of its future role in blue growth. *Rev. Aquacult.* **2019**, *11*, 493–514. [CrossRef]
120. Jolly, C.M.; Nyandat, B.; Yang, Z.; Ridler, N.; Matias, F.; Zhang, Z.; Menezes, A. Dynamics of aquaculture governance. *J. World Aquacult. Soc.* **2023**, *54*, 427–481. [CrossRef]
121. Baskaran, A.; Chandran, V.G.R.; Ng, B.K. Inclusive entrepreneurship, innovation and sustainable growth: Role of business incubators, academia and social enterprises in Asia. *Sci. Technol. Soc.* **2019**, *24*, 385–400. [CrossRef]
122. Ohia, C.M.D. Aquaculture technologies and practices: Balancing innovation, environment and economy for sustainability. In *Food Security, Nutrition and Sustainability Through Aquaculture Technologies*; Springer: Cham, Switzerland, 2025; pp. 417–424. [CrossRef]
123. Ahmed, N.; Turchini, G.M. Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *J. Clean. Prod.* **2021**, *297*, 126604. [CrossRef]
124. Badiola, M.; Basurko, O.C.; Piedrahita, R.; Hundley, P.; Mendiola, D. Energy use in Recirculating Aquaculture Systems (RAS): A review. *Aquac. Eng.* **2018**, *81*, 57–70. [CrossRef]
125. Colombo, S.M.; Roy, K.; Mraz, J.; Wan, A.H.; Davies, S.J.; Tibbetts, S.M.; Turchini, G.M. Towards achieving circularity and sustainability in feeds for farmed blue foods. *Rev. Aquacult.* **2023**, *15*, 1115–1141. [CrossRef]
126. Chen, J.; Wang, Z.; Shen, X.; Chen, R.; Peng, Y.; Cai, Y.; Ying, H. Solid-state fermentation through synthetic microbiome: An effective strategy for converting Chinese distillers' grains into functional protein feed. *Int. J. Food Microbiol.* **2025**, *435*, 111154. [CrossRef] [PubMed]
127. Hoseinifar, S.H.; Faheem, M.; Liaqat, I.; Van Doan, H.; Ghosh, K.; Ringø, E. Promising probiotic candidates for sustainable aquaculture: An updated review. *Animals* **2024**, *14*, 3644. [CrossRef] [PubMed]
128. Jiang, H.; Wang, J.; Jiang, W.; Wang, J.; Gu, X.; Feng, X.; Fang, J. Simultaneous detection of *Vibrio parahaemolyticus* and antimicrobial resistance genes using immunomagnetic separation combined with RPA-microfluidic method in seafood. *Food Cont.* **2024**, *165*, 110653. [CrossRef]
129. Intarakumnerd, P.; Chairatana, P.A.; Kamondetdacha, R. Innovation system of the seafood industry in Thailand. *Asian J. Technol. Innov.* **2015**, *23*, 271–287. [CrossRef]

130. Tongmee, B.; Unpaprom, Y.; Ramaraj, R.; Mengumphan, K.; Amornlerdpison, D. Sustainability innovation and circular economy of freshwater hybrid catfish oil extraction. *Maejo Int. J. Energy Environ. Commun.* **2023**, *5*, 35–40. [CrossRef]
131. Arulingam, I.; Nigussie, L.; Senaratna Sellamuttu, S.; Debevec, L. *Youth Participation in Small-Scale Fisheries, Aquaculture and Value Chains in Africa and the Asia-Pacific*; CGIAR Research Program on Fish Agri-Food Systems: Penang, Malaysia, 2019.
132. Janssen, K.; Saatkamp, H.; Komen, H. Cost-benefit analysis of aquaculture breeding programs. *Genet. Sel. Evol.* **2018**, *50*, 2. [CrossRef]
133. Elisha, O.D.; Felix, M.J. Destruction of coastal ecosystems and the vicious cycle of poverty in Niger Delta region. *J. Glob. Agric. Ecol.* **2021**, *11*, 7–24.
134. Emmanuel, E.I.; Asuquo, I.A.E.; Abiaobo, N.O. Threatened and endangered fish species in Nigeria, a menace to biodiversity—A review. *Afr. J. Educ. Sci. Technol.* **2016**, *3*, 12–26.
135. Okonkwo, C.N.P.; Kumar, L.; Taylor, S. The Niger Delta wetland ecosystem: What threatens it and why should we protect it? *Afr. J. Environ. Sci. Technol.* **2015**, *9*, 451–463. [CrossRef]
136. Popoola, O.M. Fish production and biodiversity conservation: An interplay for life sustenance. In *Biodiversity in Africa: Potentials, Threats and Conservation*; Chibueze Izah, S., Ed.; Springer: Berlin/Heidelberg, Germany, 2022; Volume 29. [CrossRef]
137. Nyakeya, K.; Masese, F.O.; Gichana, Z.; Nyamora, J.M.; Getabu, A.; Onchieku, J.; Nyakwama, R. Cage farming in the environmental mix of Lake Victoria: An analysis of its status, potential environmental and ecological effects, and a call for sustainability. *Aquat. Ecosyst. Health Manag.* **2022**, *25*, 37–52. [CrossRef]
138. Tiwari, A.K.; Pal, D.B. Nutrients contamination and eutrophication in the river ecosystem. In *Ecological Significance of River Ecosystems*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 203–216. [CrossRef]
139. Aransiola, S.A.; Zobeashia, S.L.T.; Ikhumetse, A.A.; Musa, O.I.; Abioye, O.P.; Ijah, U.J.J.; Maddela, N.R. Niger Delta mangrove ecosystem: Biodiversity, past and present pollution, threat and mitigation. *Reg. Stud. Mar. Sci.* **2024**, *75*, 103568. [CrossRef]
140. Modeel, S.; Dolkar, P.; Siwach, S.; Yadav, P.; Negi, R.K. Role of science and technology for sustainable aquaculture development and aquatic ecosystem management. In *Role of Science and Technology for Sustainable Future: Volume 1: Sustainable Development: A Primary Goal*; Springer: Singapore, 2024; pp. 277–301.
141. Choudhary, B.; Deb, S.; Chouhan, N.; Azmeera, S.; Choudhary, V. Integrated multi-trophic aquaculture (IMTA) for wastewater treatment and resource recovery: A sustainable approach. In *Nature-Based Technologies for Wastewater Treatment and Bioenergy Production*; IWA Publishing: London, UK, 2025; p. 77. [CrossRef]
142. Ghosh, A.K.; Hasanuzzaman, A.F.M.; Islam, S.S.; Sarower, M.G.; Mistry, S.K.; Arafat, S.T.; Huq, K.A. Integrated multi-trophic aquaculture (IMTA): Enhancing growth, production, immunological responses, and environmental management in aquaculture. *Aquacult. Int.* **2025**, *33*, 336. [CrossRef]
143. Akindele, E.O.; Ekwemuka, M.C.; Apeverga, P.; Amusa, T.O.; Olajuyigbe, S.; Coker, O.M.; Kolawole-Daniels, A. Assessing awareness on biodiversity conservation among Nigerians: The Aichi Biodiversity Target 1. *Biodivers. Conserv.* **2021**, *30*, 1947–1970. [CrossRef]
144. Domician, C.L. Improving Traceability to Achieve Sustainable Development and Commercial Scaling-Up of Fisheries Resources in Tanzania. Ph.D. Thesis, University Reading, Reading, UK, 2024. [CrossRef]
145. Saha, C.K. Emergence and evolution of aquaculture sustainability certification schemes. *Mar. Policy* **2022**, *143*, 105196. [CrossRef]
146. Yeşilsu, A.F.; Alak, G.; Alp Erbay, E.; Sağdıç, O.; Özoğul, F.; Demirkesen, İ.; Aydın, İ. Sustainable horizons: A review on sustainable processing, quality enhancement, and safety assurance in aquatic food products. *Food Rev. Int.* **2025**, *41*, 1709–1737. [CrossRef]
147. Kitinoja, L.; Tokala, V.Y.; Mohammed, M.; Mahajan, B.V.C. Cold chain and its importance—Current global status. In *Cold Chain Management for the Fresh Produce Industry in the Developing World*; CRC Press: Boca Raton, FL, USA, 2021; pp. 3–17.
148. Khan, M.A.; Hossain, M.E.; Shahaab, A.; Khan, I. ShrimpChain: A blockchain-based transparent and traceable framework to enhance the export potentiality of Bangladeshi shrimp. *Smart Agric. Technol.* **2022**, *2*, 100041. [CrossRef]
149. Ismail, S.; Reza, H.; Salameh, K.; Kashani Zadeh, H.; Vasefi, F. Toward an intelligent blockchain IoT-enabled fish supply chain: A review and conceptual framework. *Sensors* **2023**, *23*, 5136. [CrossRef]
150. Williams, M.J.; Agbayani, R.; Bhujel, R.; Bondad-Reantaso, M.G.; Brugère, C.; Choo, P.S.; Dhont, J.; Galmiche-Tejeda, A.; Ghulam, K.; Kusakabe, K.; et al. Sustaining aquaculture by developing human capacity and enhancing opportunities for women. In *Farming the waters for people and food: Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand, 22–25 September 2010*; Subasinghe, R.P., Arthur, J.R., Bartley, D.M., De Silva, S.S., Halwart, M., Hishamunda, N., Mohan, C.V., Sorgeloos, P., Eds.; FAO & NACA: Rome, Italy, 2012; pp. 785–874.
151. Barabaschi, D.; Tondelli, A.; Desiderio, F.; Volante, A.; Vaccino, P.; Valè, G.; Cattivelli, L. Next generation breeding. *Plant Sci.* **2016**, *242*, 3–13. [CrossRef]
152. Elmessery, W.M.; Abdallah, S.E.; Oraiath, A.A.T. A deep deterministic policy gradient approach for optimizing feeding rates and water quality management in recirculating aquaculture systems. *Aquacult. Int.* **2025**, *33*, 253. [CrossRef]

153. Lal, J.; Vaishnav, A.; Deb, S.; Gautam, P.; Pavankalyan, M.; Kumari, K.; Verma, D.K. Re-circulatory aquaculture systems: A pathway to sustainable fish farming. *Arch. Curr. Res. Int.* **2024**, *24*, 799–810. [CrossRef]
154. Turlybek, N.; Nurbekova, Z.; Mukhamejanova, A.; Baimurzina, B.; Kulatayeva, M.; Aubakirova, K.M.; Alikulov, Z. Sustainable aquaculture systems and their impact on fish nutritional quality. *Fishes* **2025**, *10*, 206. [CrossRef]
155. Boyd, C.E.; McNevin, A.A. An early assessment of the effectiveness of aquaculture certification and standards. *Roles Limit. Certif.* **2012**, *35*, 168–202.

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